WOLF

The Electrical Precipitation

of Particles Suspended in Gases

Electrical Engineering

M. S.

1914

THE ELECTRICAL PRECIPITATION OF
PARTICLES SUSPENDED IN GASES

BY

HERMAN CARL WOLF

B. S. University of Illinois

1913

THESIS

Submitted in Partial Fulfillment
of the Requirements for the

Degree of

MASTER OF SCIENCE

IN ELECTRICAL ENGINEERING

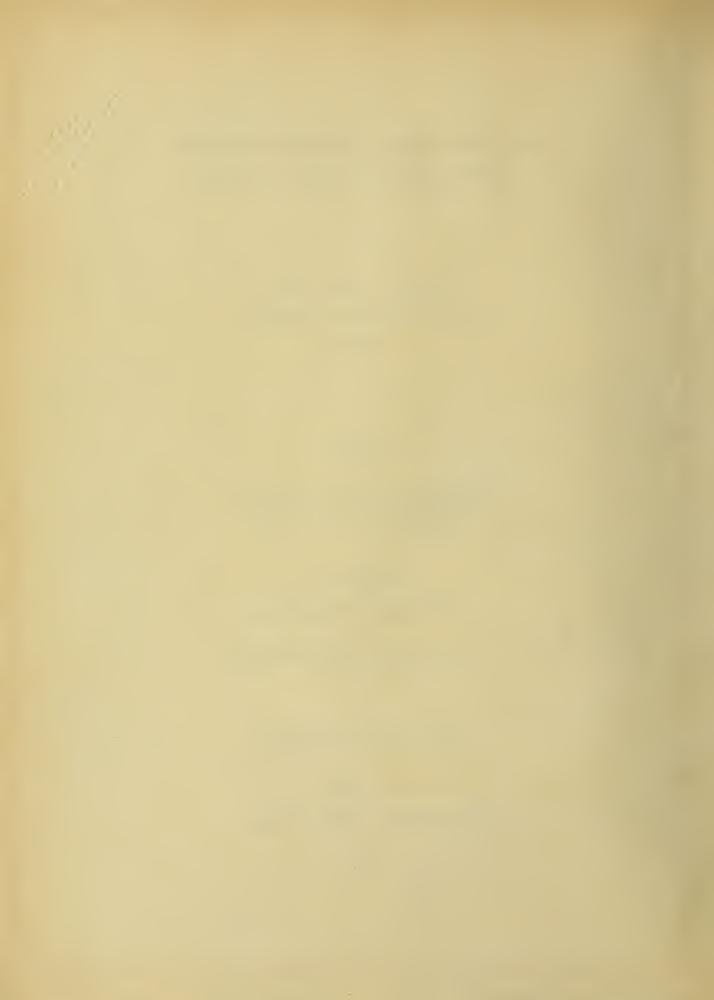IN

THE GRADUATE SCHOOL

OF THE

UNIVERSITY OF ILLINOIS

1914

UNIVERSITY OF ILLINOIS

THE GRADUATE SCHOOL

June 1   1914

I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Herman Carl Wolf

ENTITLED   The Electrical Precipitation of Particles

Suspended in Cases

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE

DEGREE OF Master of Science in Electrical Engineering

Ellery B. Paine.

In Charge of Major Work

Ellery B. Paine.

Head of Department

Recommendation concurred in:

Morgan Brooks.

J. M. Bryant

C. W. H. Waldo.

} Committee on Final Examination

TABLE OF CONTENTS.

-------- O ------- O --------

INDEX TO FIGURES.

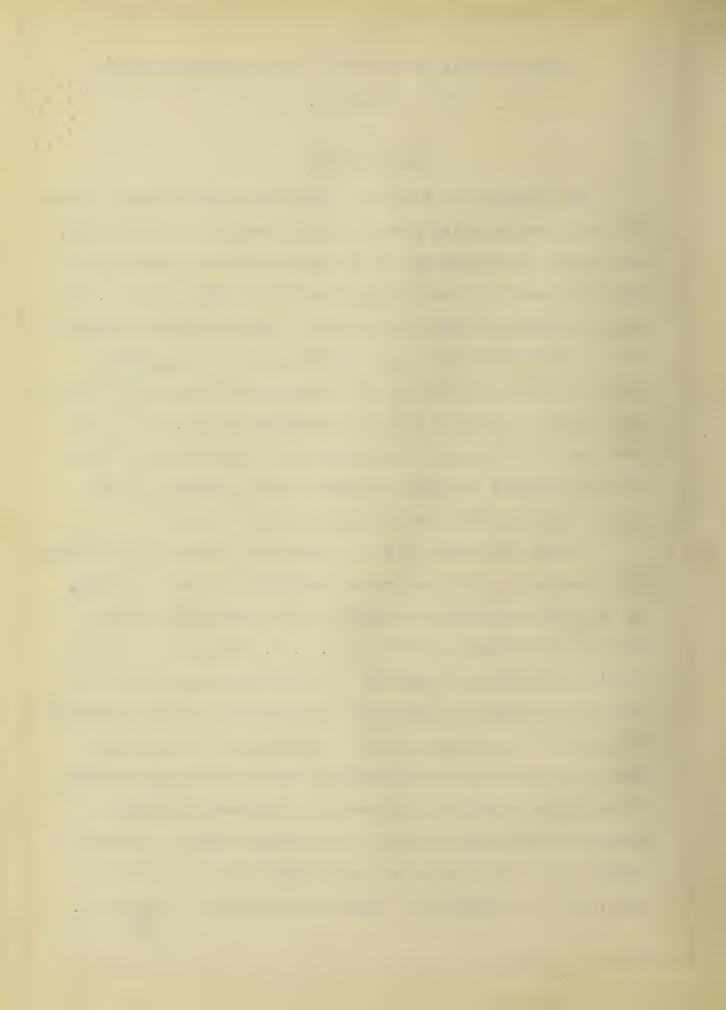----- o ----- o ----- o ----- o -----

THE ELECTRICAL PRECIPITATION OF PARTICLES SUSPENDED IN GASES.

I

Introduction.

The presence of heavy and obnoxious fumes in the vicinity of large manufacturing plants, such as smelters and refiners, has caused investigations to be made in order to determine an efficient means of lessening the evils attendant thereon. The growing tendency toward the universal application of electricity and the ease with which high voltages may be obtained has caused a revival of process for precipitating suspended particles from gases by means of high electromotive forces. The idea of such precipitation was first suggested by Hohlfield in 1824, later by Guitard in 1849, and was put into practice by Sir Oliver Lodge in 1886 for clearing the air of fog.

Lodge first made use of a Wimshurst machine for charging the atmosphere, but this proved unsatisfactory and, in 1903, he employed a mercury-arc rectifier for obtaining high uni-directional voltages. In 1907, Dr. F. G. Cottrell of the University of California employed a rotating contact maker, or voltage rectifier for obtaining unidirectional from alternating voltage, and as a result of this application, succeeded in putting the process into commercial use for the precipitation of particles suspended in gases. The problems of voltage generation and rectification, of efficient forms for precipitators, and of the scope and application of the process are many, and it is these that form the context for this thesis.
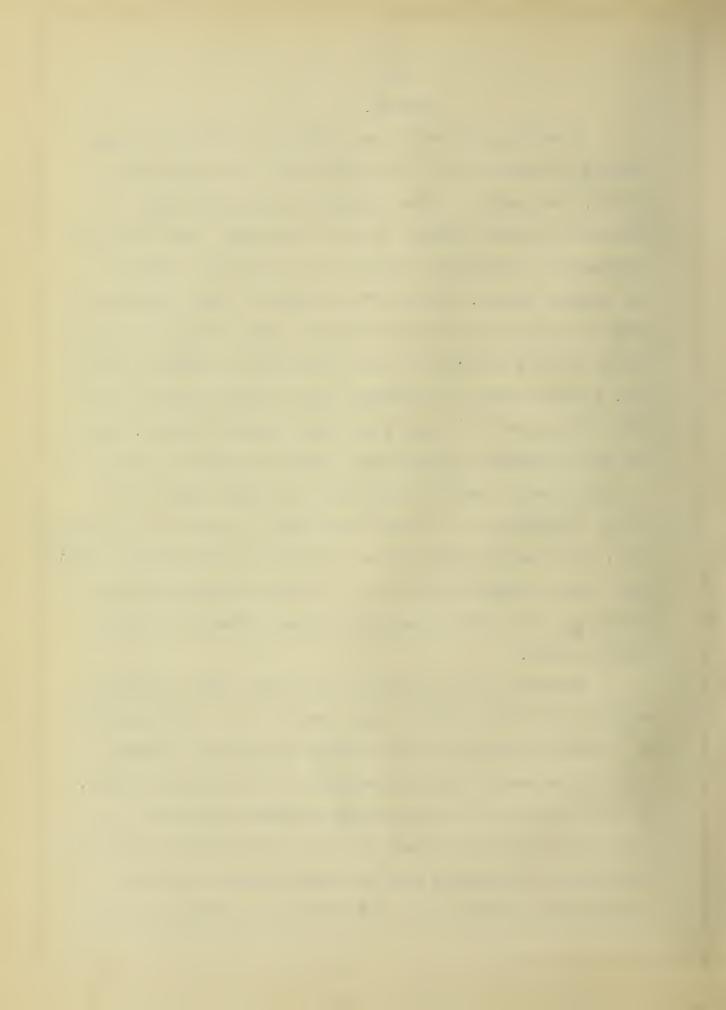
II.

Theory.

A voltage applied to any system of electrodes causes charges of electricity to be given off to the surrounding medium. The number of these charges is dependent upon the potential gradient between the two electrodes, upon the temperature and atmospheric pressure, and upon the nature of the gaseous medium. These charges travel on ions, negative from the negative electrode- positive from the positive electrode, and are attracted by the electrodes of opposite polarity. A point source of discharge has a higher surface intensity, hence gives off more ions than a smooth surface. Thus, the medium between a point and a plate of opposite polarity is charged more heavily with ions of the same sign as the point, irrespective of whether that sign is positive or negative. Any insulated body, free to move, brought into this field, will travel toward the plate at a velocity proportional to its charge and to the potential gradient between the point and the plate.
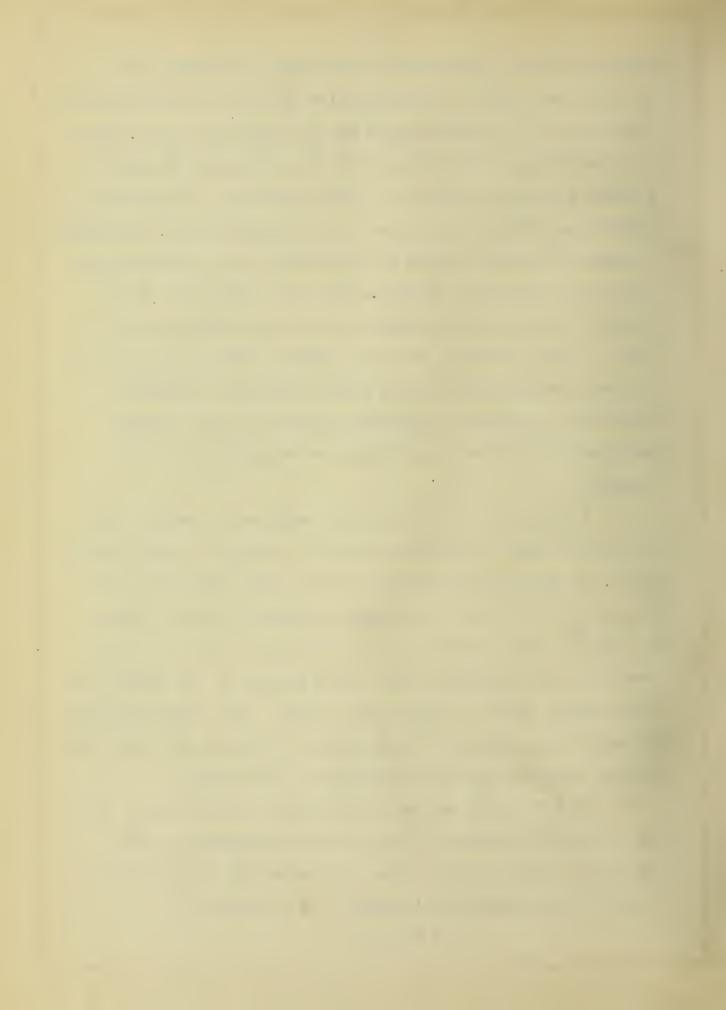
Negative ions are smaller and travel with a greater velocity than the positive ones, hence, when a unidirectional voltage is applied to two similar electrodes, a strong circulation results from the negative to the positive poles. If the medium is a gas containing suspended particles, the ions strike these particles, give up a part of their charges, and cause the particles also to travel toward the pole of opposite sign. Coming into contact with one another, unlike

charges attract , agglomerate into larger particles, and fall
of their own weight. Those particles which are not agglomerated
travel on to the opposite pole and are deposited there. When
an alternating voltage is applied, the reversals of polarity
prevent a strong circulation in one direction, and hence the
depositing effect is only that due to agglomeration. According-
ly, more efficient results are obtainable with unidirectional
than with alternating voltage. Since the efficiency of the
process depends upon the emmission of the greatest number of
ions, in one direction, with the highest surface tension, for
the least voltage applied and power consumed, a system of
points as a negative or discharge electrode and of smooth
surfaces as positive or collecting electrodes is the most
feasible.

A unit charge is that charge which will exert a force
of one dyne upon a similar charge at a distance of one centi-
meter. It may also be defined as that charge which will pro-
duce one line of force per square centimeter on the surface
of a sphere with a radius of one centimeter. Hence the total
number of lines of force from a unit charge is 4π while the
total number due to a charge "Q" is thus $4\pi Q$. This quantity
is numerically equal to the product of the force per unit area
and the area, or the total electrical force acting.

If "r" is the radius of a cylinder, or of a wire, "K",
the dielectric constant of the medium surrounding it, and
"p" the intensity of the force, the number of lines of force
given off per centimeter length of the cylinder is

$$2\pi K r p.$$

Equating the two equal values,

$$4 \pi Q = 2 \pi K r p \qquad (1)$$

Or

$$p = \frac{2Q}{K r} \qquad (2)$$

The potential of a point is defined as the amount of work required to bring a unit charge from infinity up to that point, while the difference in potential between two points is the difference in the work required to bring the unit charge from infinity to each of the points. Hence, the difference in potential between two points, "dw" , at a distance " dr " from each other, is
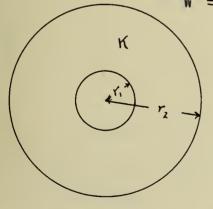
$$dw = p \, dr \qquad (3)$$

Then

$$W = p_2 - p_1 = \int_{r_1}^{r_2} p \, dr \qquad (4)$$

where p_1 and p_2 are the potentials at the two points r_1 and r_2 respectively. Substituting (2) in (4) ,

$$W = P = \frac{2Q}{K} \int_{r_1}^{r_2} \frac{dr}{r} \qquad (5)$$
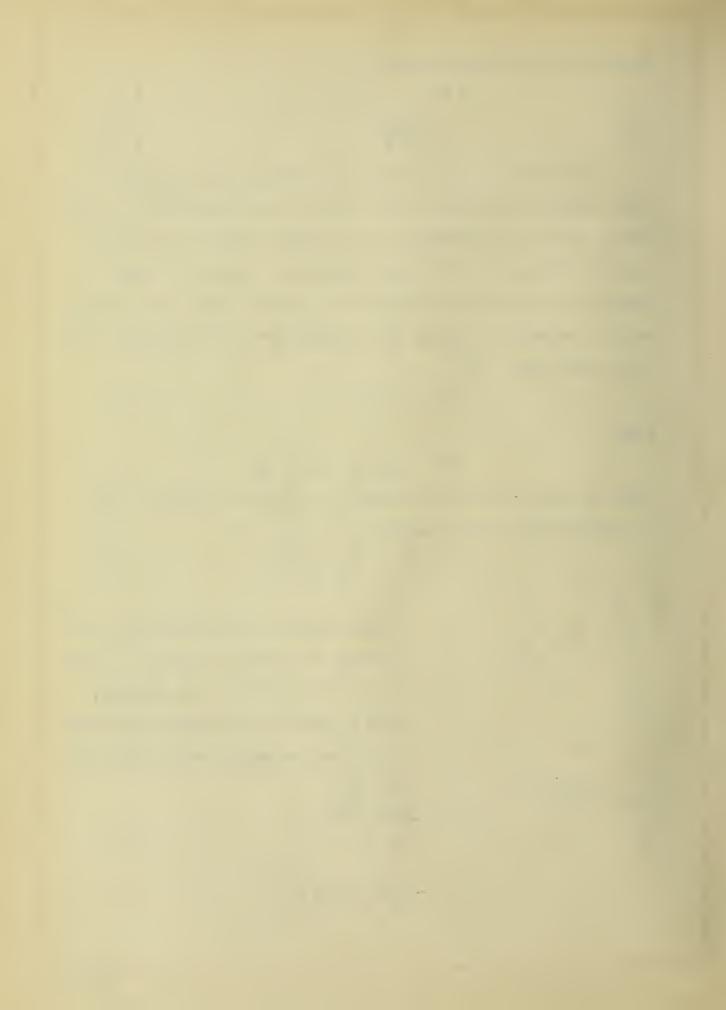

Figure 1.

If we consider two concentric cylinders, as shown in Figure 1, where r_1 is the radius of the smaller, and r_2 that of the larger, and with a dielectric medium whose constant is "K",

$$P = \frac{2Q}{K} \int_{r_1}^{r_2} \frac{dr}{r} \qquad (6)$$

$$= \frac{2Q}{K} \log_e r \Big]_{r_1}^{r_2}$$

$$P = \frac{2Q}{K} \log_e \frac{r_2}{r_1} \qquad (7)$$

But the charge given off is proportional to the difference in potential and to the capacity, or

$$Q = C_x P \qquad (8)$$

where " C " is the capacity per unit length, " P " is the difference in potential between the cylinders, and all quantities are expressed in appropriate units.

Solving (7) and (8) for " P ", and equating results,

$$\frac{Q}{C} = \frac{2Q}{K} \log_e \frac{r_2}{r_1} \qquad (9)$$

Or

$$C = \frac{K}{2 \log_e \frac{r_2}{r_1}} \qquad (10)$$

expressed in electrostatic units.

Reducing the expression to farads per centimeter,

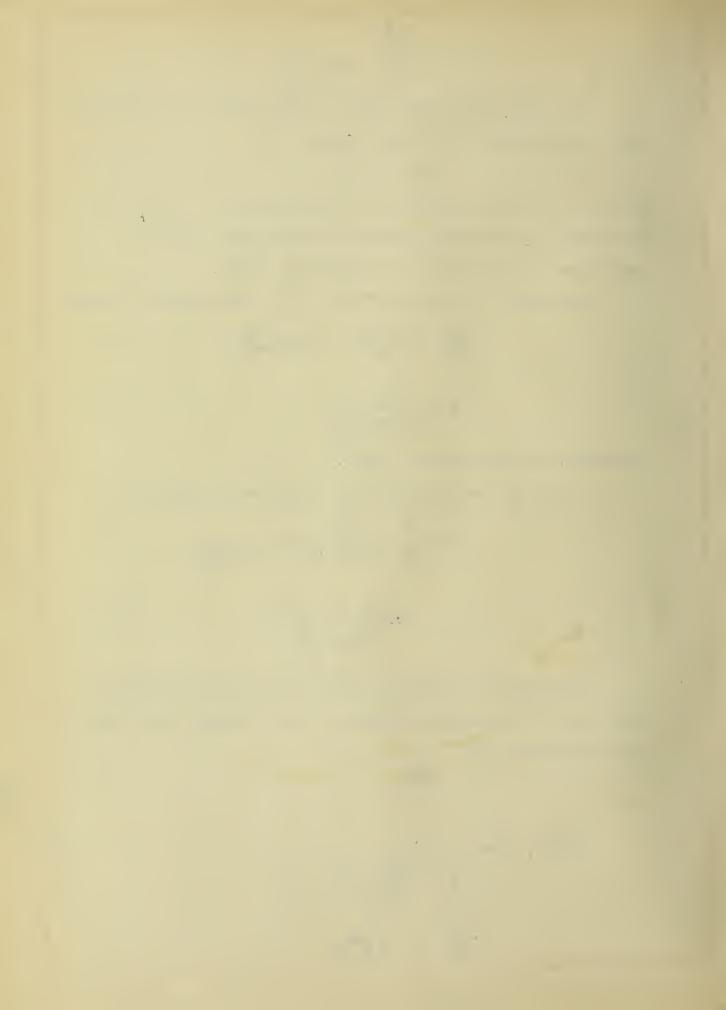$$C = \frac{K \quad 10^9}{(\mathbf{3}_x 10^{10})^2 \; 2 \; \log \frac{r_2}{r_1}}$$

or

$$C = \frac{.555 \; K \; 10^{-12}}{\log_e \frac{r_2}{r_1}} \qquad (11)$$

The potential gradient between two charged bodies is the ratio of the drop in voltage to the distance over which the drop occurs, or

$$\frac{dP}{dr}.$$

Since, from (5),

$$P = \frac{2Q}{K} \int \frac{dr}{r}$$

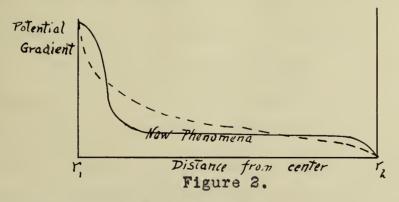$$\frac{dP}{dr} = \frac{2Q}{K \; r} \qquad (12)$$

at the surface of the conductor. At any other point in the
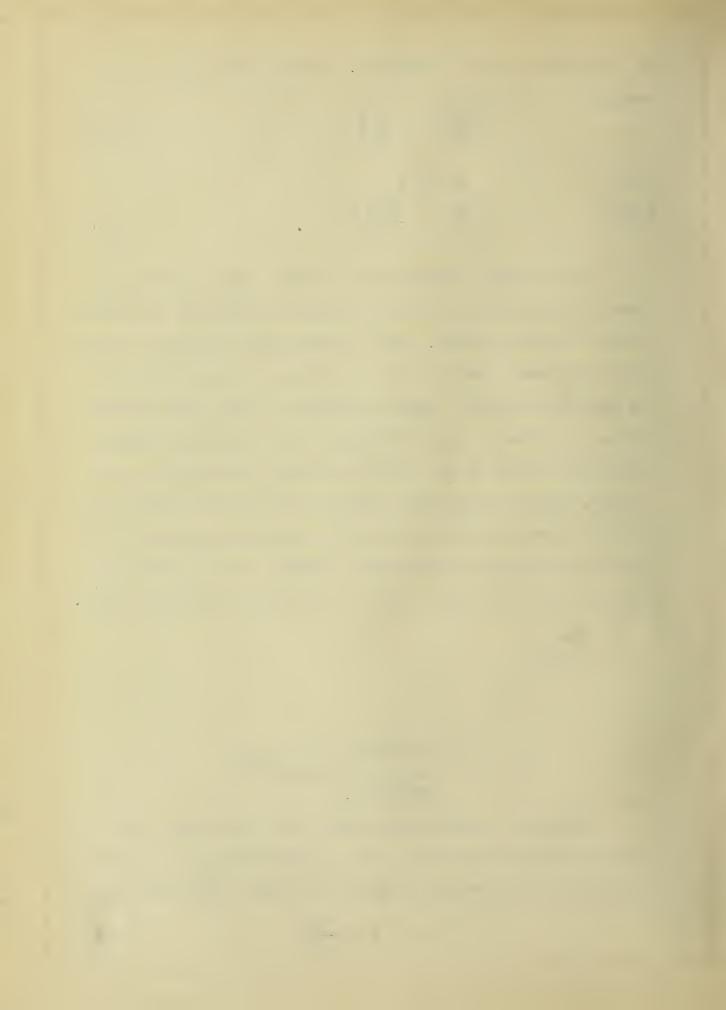medium

$$\frac{dP}{dr} = \frac{2\,Q}{K\,x}$$ (13)

But $$Q = C\,E$$

hence, $$\frac{dP}{dr} = \frac{2\,C\,E}{K\,x}$$ (14)

In the above development, it has been assumed that
lines of equipotential are concentric and diminish regularly
from the inner cylinder. Recent experiments conducted at this
University have shown this to be untrue, but that the lines
are more concentrated near the surface of the inner cylinder
and are practically equal throughout the intervening space,
until, very close to the outer cylinder, they diminish very
rapidly. Figure 2 shows the comparative relation between the
distance from the electrodes and the potential gradient. The
dotted line follows the principle assumed in the above dis-
cussion, while the solid line is the relation recently found.

Figure 2.

Since the velocity with which the ions travel from
negative points to positive plates is proportional to their
charge and to the potential gradient between the electrodes,

$$V = k\,Q\,\frac{dP}{dr}$$ (15)

where "V" is the velocity of ion travel and "k", a constant
depending upon the character of the gases and upon the air
pressure. Then

$$V = k K \frac{2 Q}{K r}$$

$$= k 2 \frac{Q^2}{Kr}$$

$$= \frac{2 k C^2 E^2}{K r} \qquad (16)$$

since

$$Q = C E$$

It is thus seen that for a given system of electrodes, the
velocity of precipitation is proportional to the square of
the impressed voltage.

Hittorf has found that the velocity of ion travel from
negative to positive point electrodes in quiescent air, is
about 2×10^5 centimeters per second, or about equal to
the square root of the velocity of light. J. J. Thomson has
found that the mechanical pressure on air at the surface of
an electrode is about 400 dynes per square centimeter at an
air pressure of 760 millimeters of mercury.

It has been found that ordinary air will stand a stress
of approximately 100,000 volts, maximum value, per centimeter,
which, then, is its potential gradient at the breaking point.
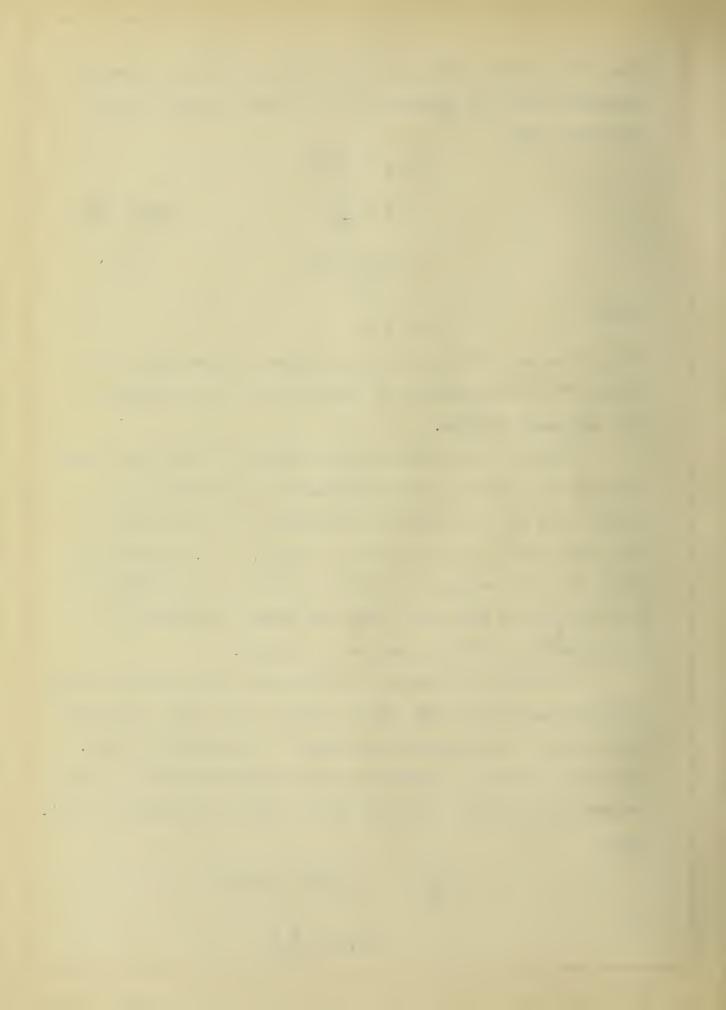In order to find the approximate flash-over point for the two
concentric cylinders, substitute this value in Equation (14).
Then

$$\frac{dP}{dr} = \frac{2 C E}{K x} = 100,000$$

or

$$E = 100,000 \frac{K x}{2 C}$$

Substituting the value of " C " as found in Equation (10),
we find that

$$E = 100,000 \frac{\log_e \frac{r_2}{r_1}}{x}$$

and, since the maximum stress is thus greatest for the smallest
value of " x ", it occurs when $x = r_1$ and

$$E_{max.} = 100,000 \frac{\log_e \frac{r_2}{r_1}}{r_1} \qquad (17)$$

In considering a system of parallel wires and plates
for precipitating electrodes, we might assume the wires to be
close enough together to form a continuous plate. If " w " is
the width of this plate and " l " the distance between electrodes
of opposite polarity, the number of lines of force per centi-
meter length of the plate is

$$p \, w \, K.$$

Similarly as before, the lines of force due to a charge " Q "
are $4 \, \pi \, Q,$

hence,

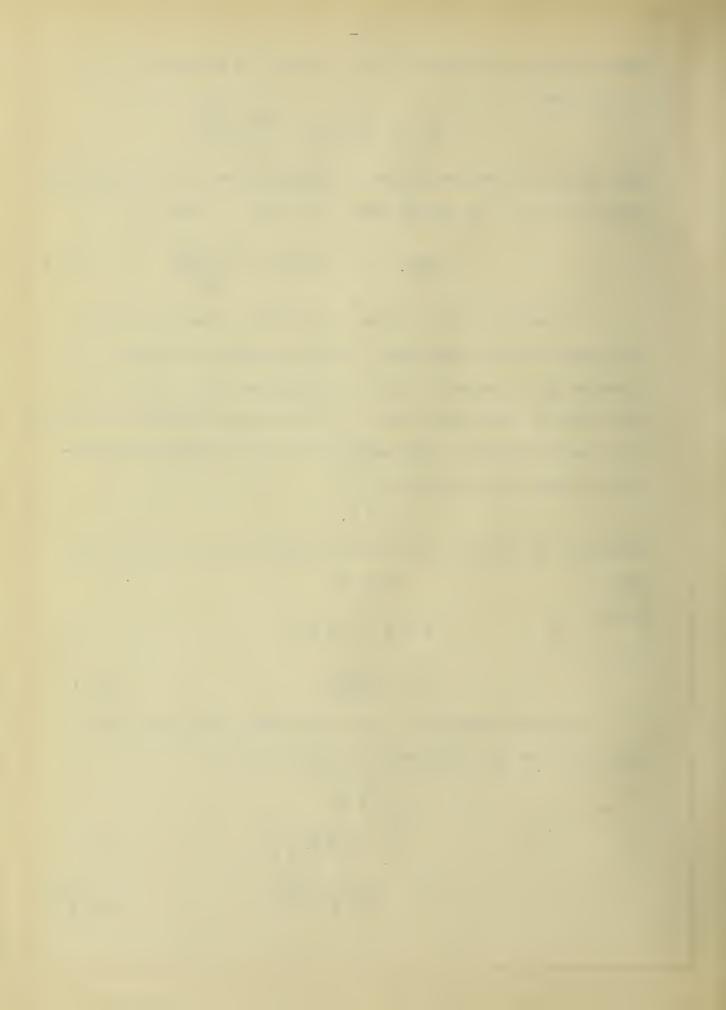$$4 \, \pi \, Q = p \, w \, K$$

or

$$p = \frac{4 \, \pi \, Q}{w \, K} \qquad (18)$$

The work required to move the charge from one plate to
the other, or the difference in potential, is

$$P = \int_0^\ell p \, dr$$

$$= \frac{4 \, \pi \, Q}{w \, K} \int_0^\ell dr \qquad (19)$$

$$\frac{4 \, \pi \, Q \, \ell}{w \, K} \qquad (20)$$

Since $\qquad\qquad\qquad\qquad Q = C\ P$

$$C = \frac{K\ w}{4\ \pi\ \ell} \qquad\qquad (\ 21\ )$$

in electrostatic units per centimeter length of plate, or

$$C = \frac{.088\ \times\ 10^{-12}\ K\ w}{\ell} \qquad\qquad (\ 22\ )$$

farads per centimeter length of plate.

From Equation (19) we can deduce the expression for the potential gradient as

$$\frac{dP}{dr} = \frac{4\ \pi\ Q}{w\ K} \qquad\qquad (\ 23\ )$$
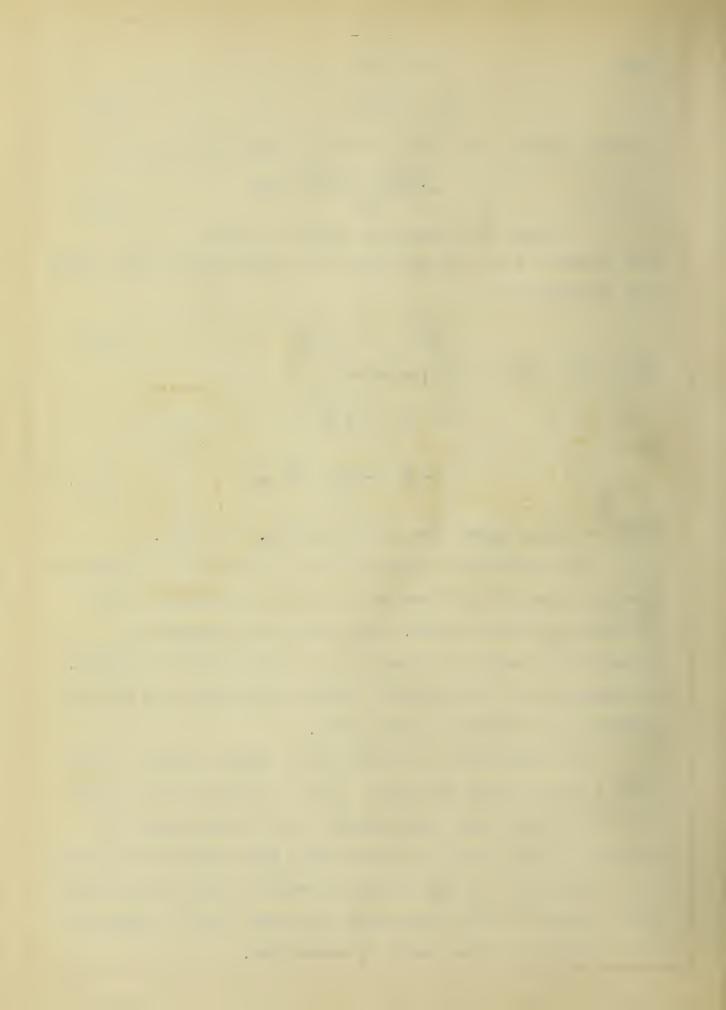
Hence, the velocity of precipitation is

$$V = k\ \frac{4\ \pi\ Q^2}{w\ K}$$

$$= \frac{k}{K}\ \times\ \frac{4}{w}\ \times\ C^2\ \times\ E^2 \qquad\qquad (\ 24\ )$$

where the same symbols are used as before, in (16).

The similarity of expressions (16) and (24) indicates that the parallel plate system is simply an extension of the concentric cylinder system. This similarity becomes more marked as the number of wires in the former system is reduced. The character of the electrode surfaces in either case greatly influences the results derived above.

The force due to the velocity of gases through a flue tends to carry along particles   after they have been agglomerated and deposited. The resultant force acting upon the particles is that due to the electrical force and to the inertia of the particles, so that the importance of using long precipitation chambers and of increasing the length with an increase in the velocity of the gases, is emphasized.

III.

-APPARATUS USED.

The apparatus used in these experiments consisted of
a 45 kilowatt motor-generator set, a 100 kilowatt, 500-1000-
2000 / 200,000 volt, 60 cycle transformer, a rotary voltage
rectifier driven by a 10 horse-power motor running in synchro-
nism with the primary circuit, and a precipitator. Figure 3
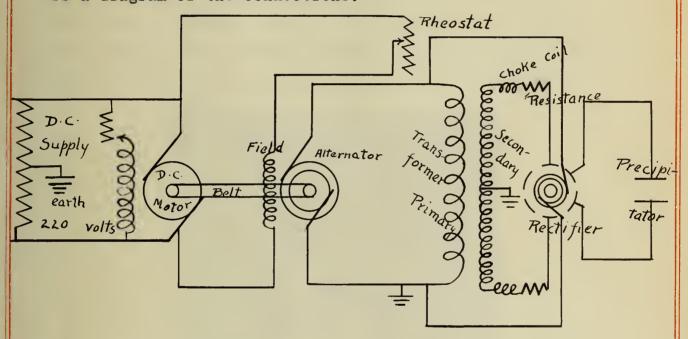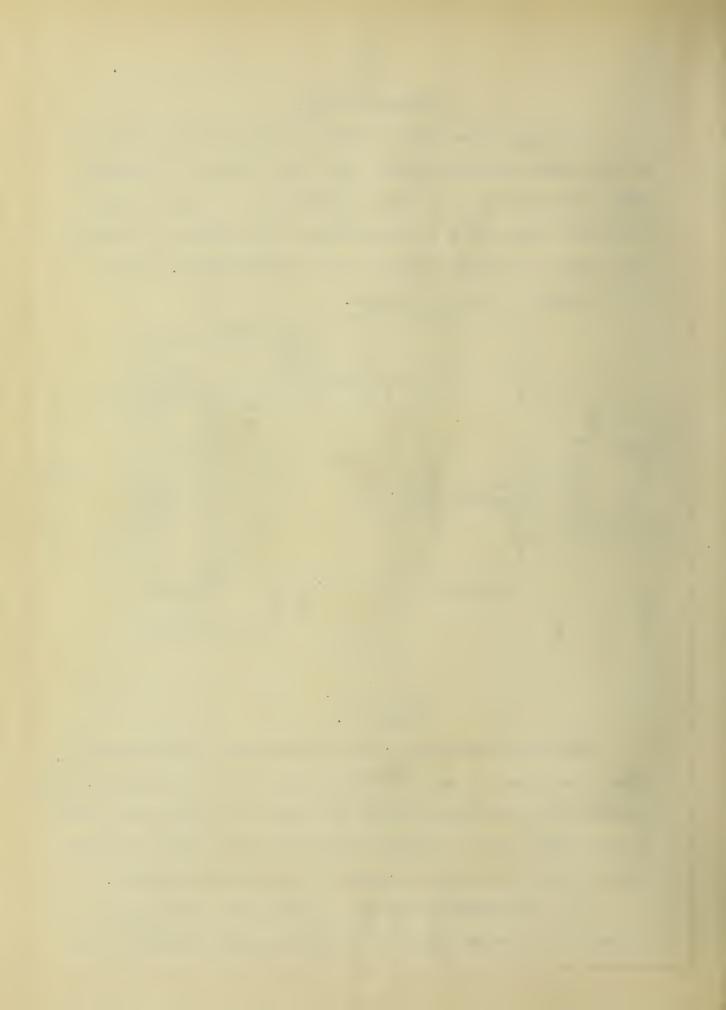is a diagram of the connections.

Figure 3.

The motor-generator set was much larger than was nec-
essary, but was the most available machine for the purpose. The
frequency of alternation could be controlled through the field
of the motor, and the voltage through the field of the alter-
nator, both by rheostats mounted on the main switchboard.

It is noticeable that all circuits were thoroughly
grounded, the center point of the high tension winding of the

transformer being grounded permanently to the core, which
in turn was connected to earth.

a - Transformer.

Figure 4 is a view of the transformer, choke coils, and
switchboard, all contained in a separate room. This room was
lined on all sides with an iron grating which, together with
all metal parts in the room, was thoroughly grounded. The
rectifier was placed upon the platform shown in the rear, and
the unidirectional voltage carried from here out through the
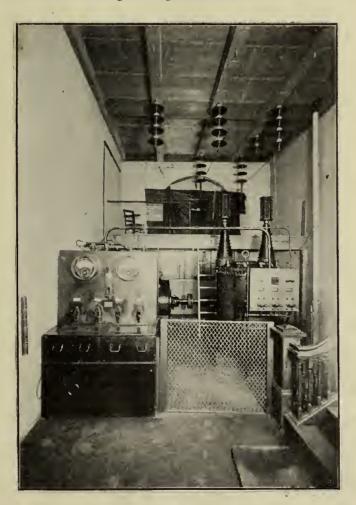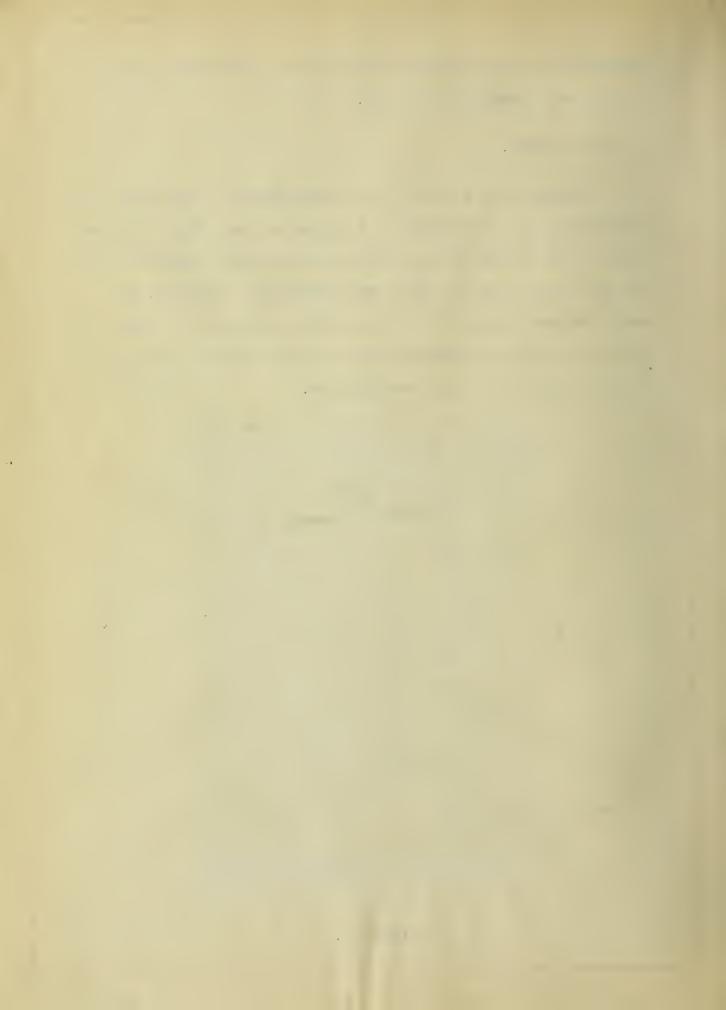rear of the room to the precipitator.

Figure 4.

Figure 5 is a diagrammatic sketch of the switchboard
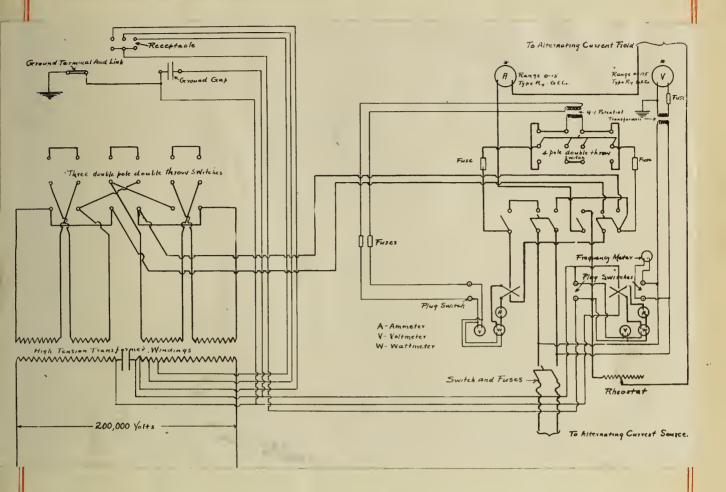and transformer connections.
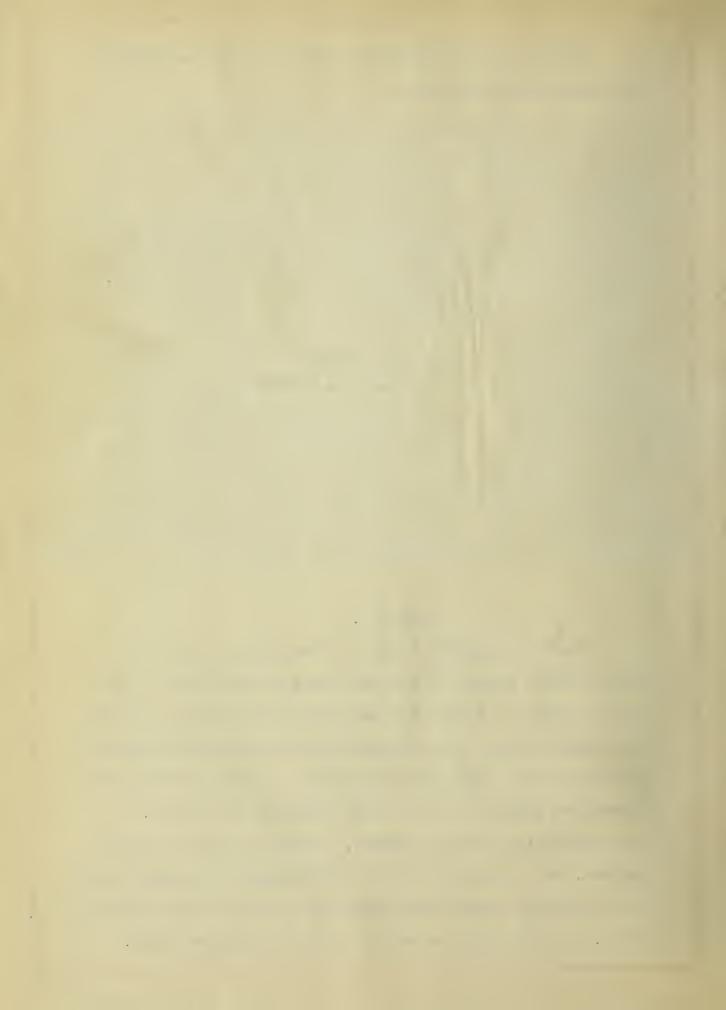
Figure 5.

Power is supplied from the alternator, driven by a
direct current motor, to the main switchboard shown at the
left in Figure 4. Meters for measuring the voltage, current,
power and frequency are contained in glass-covered drawers in
the front of the board and connections so made that when the
drawers are pulled out, all meter circuits are broken. A
short-circuiting switch, however, leaves the other circuits
complete. One single-pole and two double-pole switches control
the alternating supply and distribute current to the various
meters. A single-pole switch is in the alternator field.

From the main switchboard, power is carried to the auxiliary
board shown at the right in Figure 4, where an arrangement of
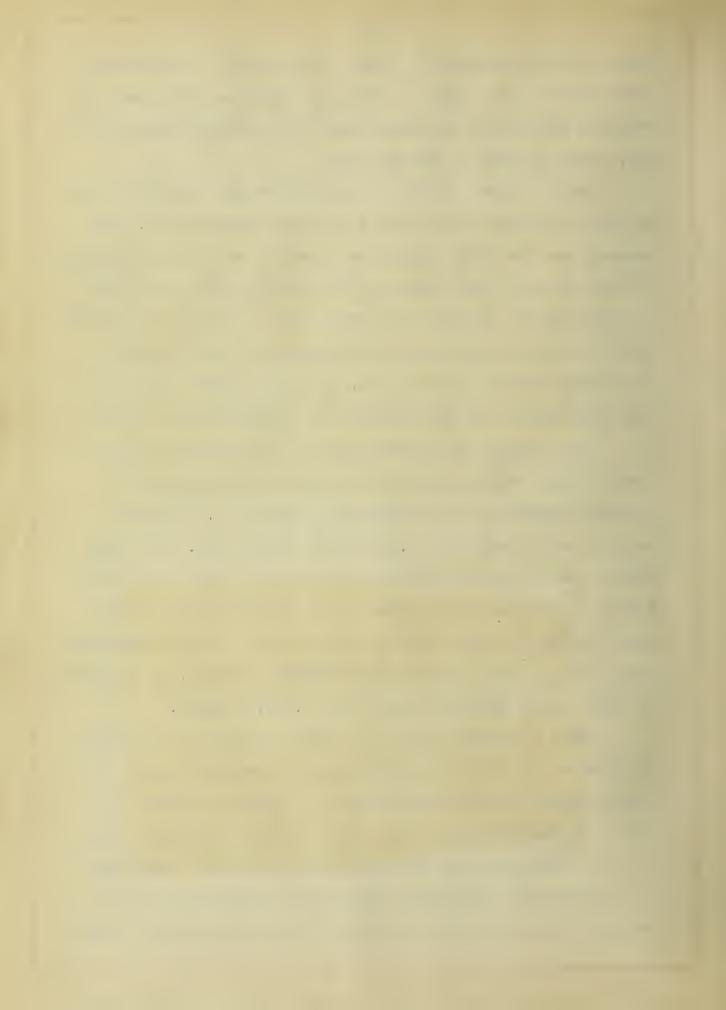switches permits of the transformer ratio being changed from
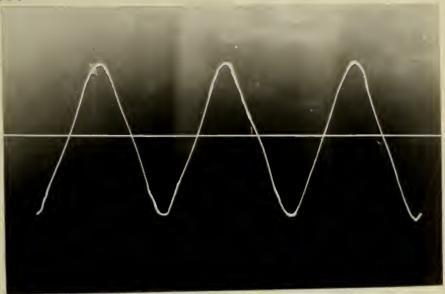500, 1000, or 2000 to 200000 volts.

An auxiliary winding is provided on the secondary side
of the transformer to be used in voltage measurements. The
connections from this winding are taken to a sorting receptacle
on the auxiliary board where a ratio of 200,000 to 400, 200,
or 100 volts may be obtained. This lower voltage is then taken
back to the main board where the frequency, watts, current,
and voltage may be read from it. An ammeter shunt gap and an
auxiliary ground gap are provided in this secondary winding.

The voltage wave taken from the 45 kilowatt generator
used for this work was somewhat distorted. An analysis of
the wave showed that its effective value was .672 of its
maximum value instead of .707 as in a sine wave. The trans-
former itself had practically no distorting effect on the wave.
Figure 6 shows two waves taken on the secondary side when no
power was being taken from the transformer, the voltages being
respectively 70,000 and 150,000, effective values. An analysis
of these waves shows the same ratio, .672, to exist.
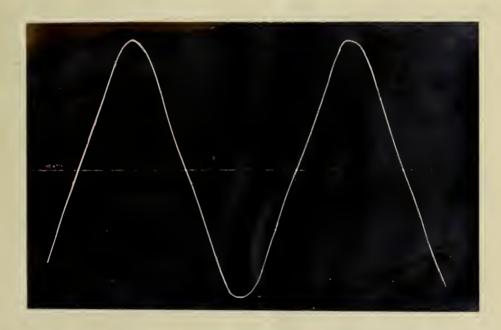
When a voltage near the disruptive value is impressed
on a series of electrodes, occasional flash-overs occur, and
high frequency oscillations follow. In order to reduce the
effect of these surges and to limit the rush of current inci-
dent to flash-overs, an air-cored inductance coil and a set
of flake-graphite resistance rods were placed in each high
tension line between the transformer and the rectifier. Later
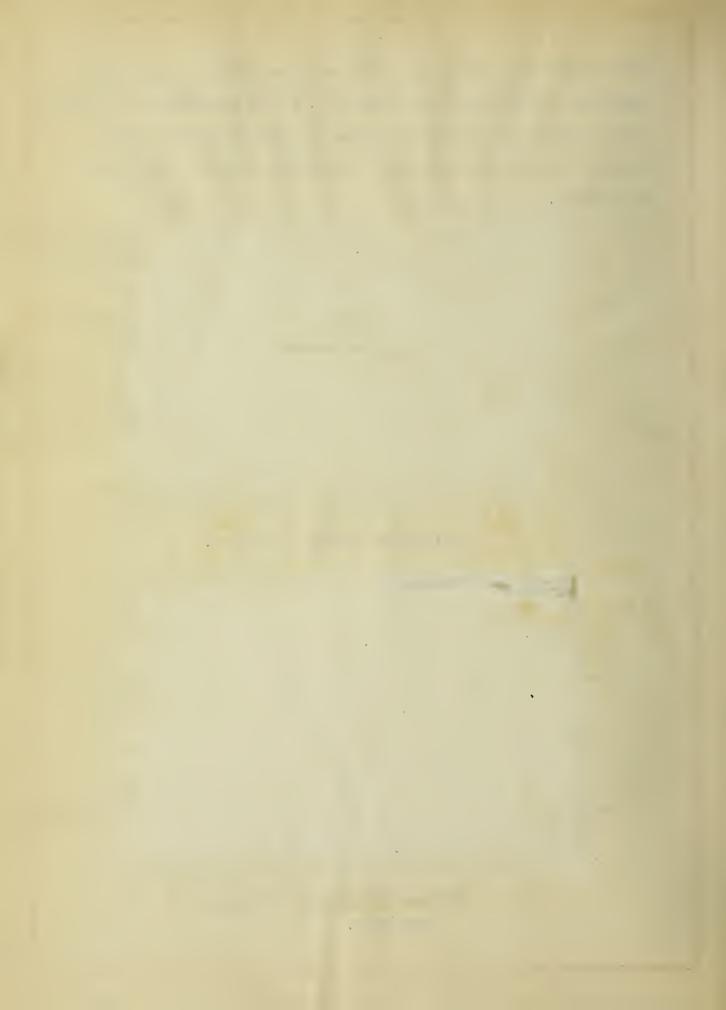
tests showed the choke coils to have less effect than might be
imagined, hence they were discarded. It is reasonable to believe
that a very large number of turns on a coil, or the use of
an iron core would be an aid in reducing the evil effects of
the surges.

Effective Voltage - 70,000.

Effective Voltage - 150,000.
Figure 6.

b - Rectfiers.

Three distinct types of voltage rectifiers were used, each designed to rectify a portion of the alternating wave and each possessing its peculiar advantages. A 10 horse-power, two phase, 4 pole, 1800 R.P.M., synchronous motor (started on both phases, but operated single phase) was used to drive the rectifiers, but a much smaller motor could well have been employed. A flexible leather coupling joined the motor to the rectifier.

A sketch of the first type of rectifier is given in Figure 7.

Figure 7.

This is of the brush-contact, disc type, alternating
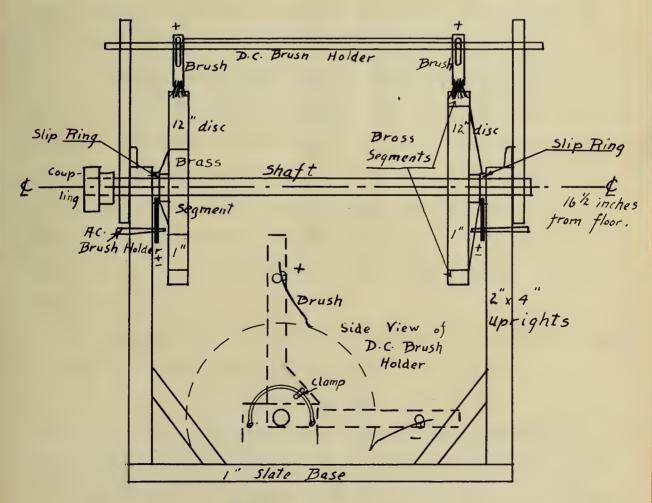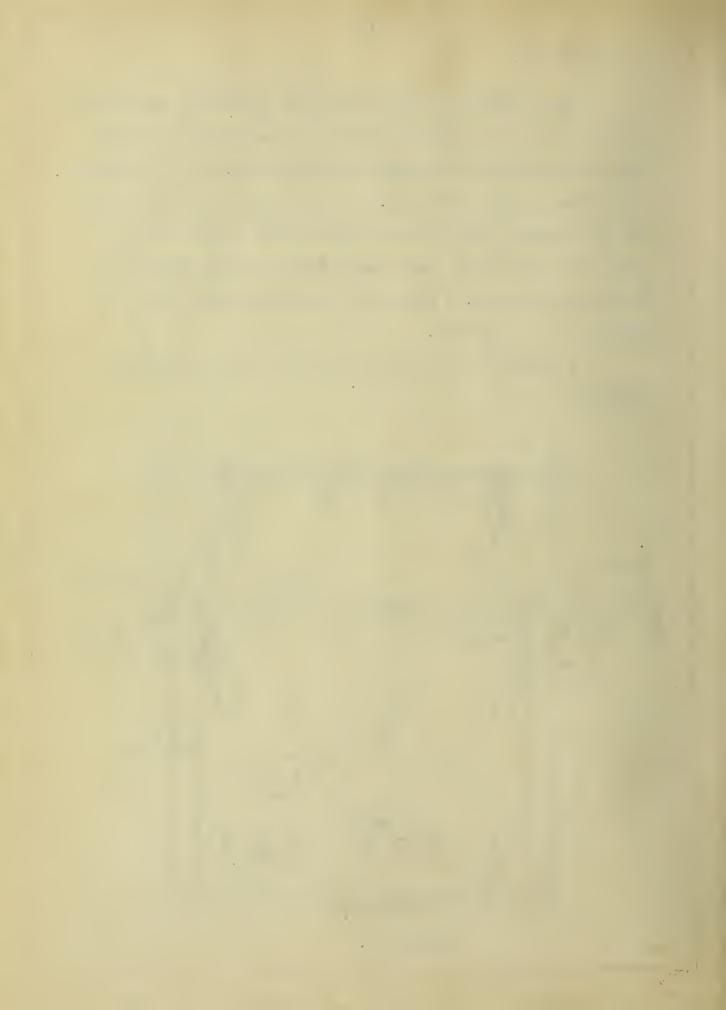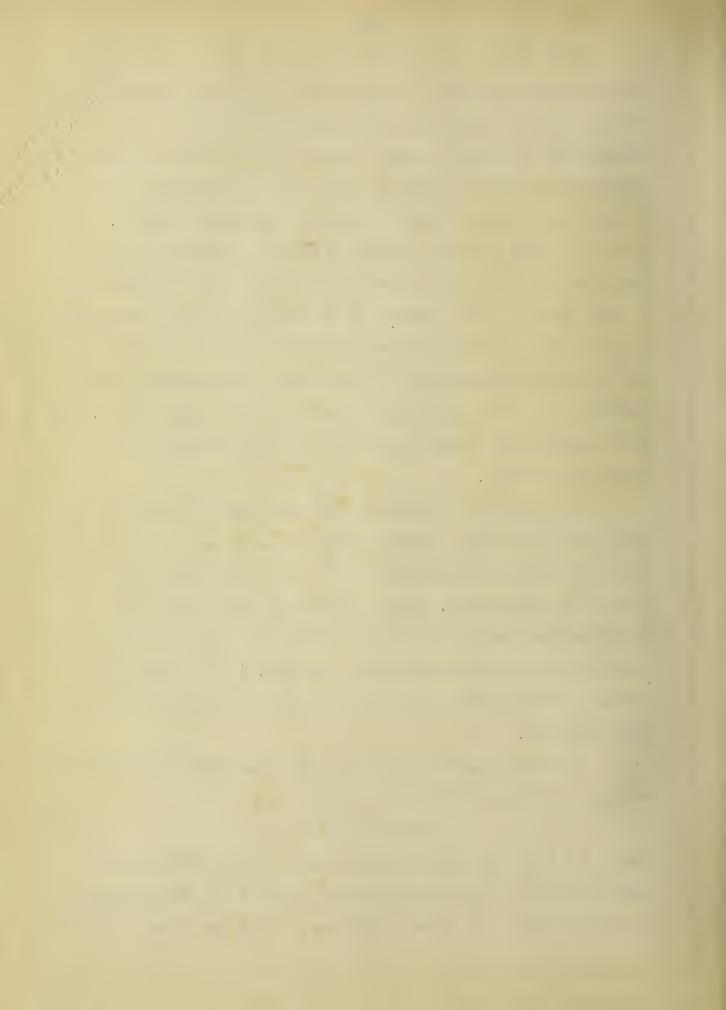voltage being brought to segments on the discs through brushes
which bear on slip-rings at the outside of the two discs. Uni-
directional voltage is taken from two sets of two brushes each,
which bear directly on the periphery of the discs and are
brought into contact with the segments embedded thereon. The
discs are hard poplar, thoroughly dried and cross-grained to
increase their strength. They are 12 inches in diameter and
1 inch thick, and are pinned to an oaken axle which revolves
in hard maple bearings. Brass segments, of such length that
90° of the impressed wave is rectified, are imbedded in the
periphery of the discs, being flush with a 12 inch circle. Two
wire brushes, 90° apart, bear on the discs and take off the
rectified voltage.

The particular advantage of this type of rectifier
lies in the fact that oscillograms may be taken on it, and its
action thoroughly studied before it is actually put into prac-
tice on high voltages. Figure 8 shows an oscillogram of the
rectified and impressed voltages from this machine (the two
waves being to different scales, however.) It is seen that
the most advantageous portion of the wave, from 45° to 135° ,
was taken off.

In analyzing this wave, let us assume that the impressed
voltage is a pure sine wave, so that

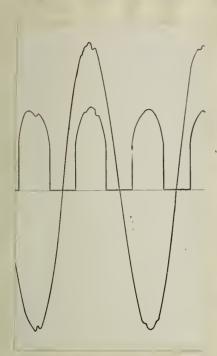$$e = E \sin \phi \hspace{3cm} (25)$$

where " e " is the instantaneous value of the electromotive
force, and " E " its maximum value, while " Θ " is the angle
of displacement. As is seen from the oscillogram, some higher

harmonics occur, but their effect happens to be very slight. By definition, the effective value of an oscillating wave is

$$E_{eff.} = \sqrt{\text{mean } e^2} \qquad (26)$$

so the effective value of the rectified wave over 180° is

$$E_{eff.} = \sqrt{\frac{1}{\pi} \int_{\frac{\pi}{4}}^{\frac{3\pi}{4}} E^2 \sin^2 \theta \, d\theta} \qquad (27)$$

But,

$$\int \sin^2 \theta \, d\theta = \frac{1}{2} \int \{1 - \cos 2\theta\} \, d\theta$$

$$= \frac{1}{2} \left\{ d\theta - \frac{1}{2} d \sin 2\theta \right\}$$

$$= \frac{\theta}{2} - \frac{\sin 2\theta}{4}$$

$$= \frac{\theta}{2} - \frac{\sin \theta \cos \theta}{2} \qquad (28)$$

Substituting (28) in (27)

$$E_{eff.} = \sqrt{\frac{E^2}{\pi} \left\{ \frac{\theta}{2} - \frac{\sin \theta \cos \theta}{2} \right\}_{\pi/4}^{\frac{3\pi}{4}}}$$

$$= E \sqrt{\left(\frac{3\pi}{8} - \frac{\pi}{8} + \frac{1}{4} + \frac{1}{4} \right) \frac{1}{\pi}}$$

$$= E \sqrt{.408}$$

$$= .64 \ E \qquad (29)$$

Figure 8.

Then a voltmeter of the induction type on the rectified side would read .64 of the maximum value of the wave, when the portion shown is taken off. An actual test gave a ratio of .639.
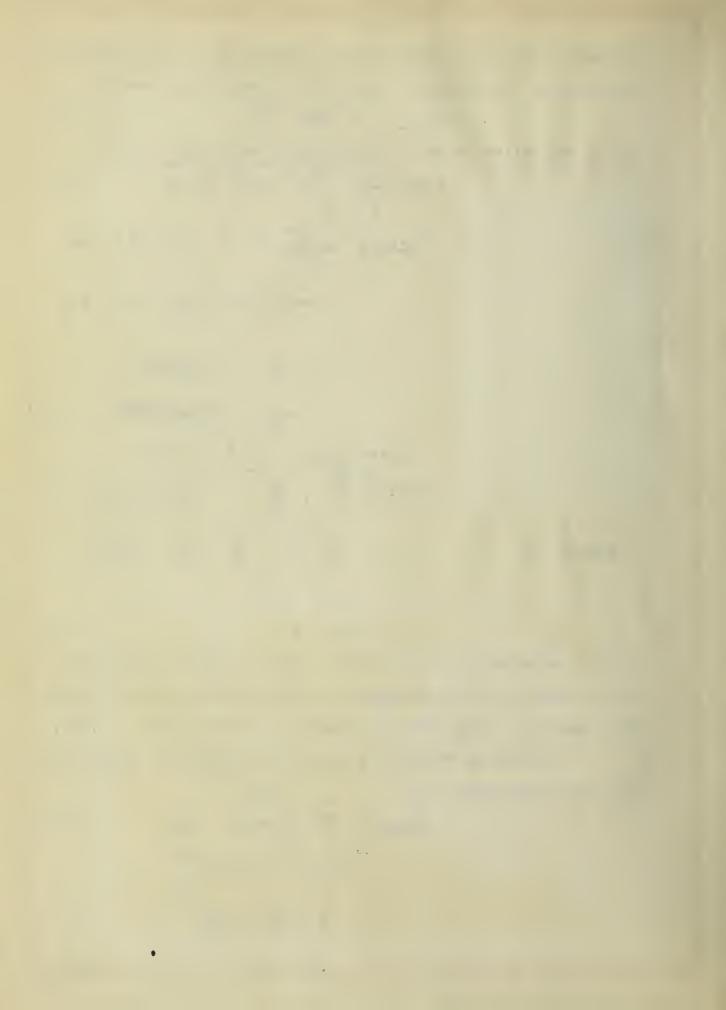
The average value of a sine wave between the same limits as considered above, is

$$E_{ave.} = \frac{E}{\pi} \int_{\frac{\pi}{4}}^{\frac{3\pi}{4}} \sin \theta \, d\theta \qquad (30)$$

$$= \frac{E}{\pi} \left[-\cos \theta \right]_{\frac{\pi}{4}}^{\frac{3\pi}{4}}$$

$$= \frac{E}{\pi} \left[\frac{1}{\sqrt{2}} + \frac{1}{\sqrt{2}} \right]$$
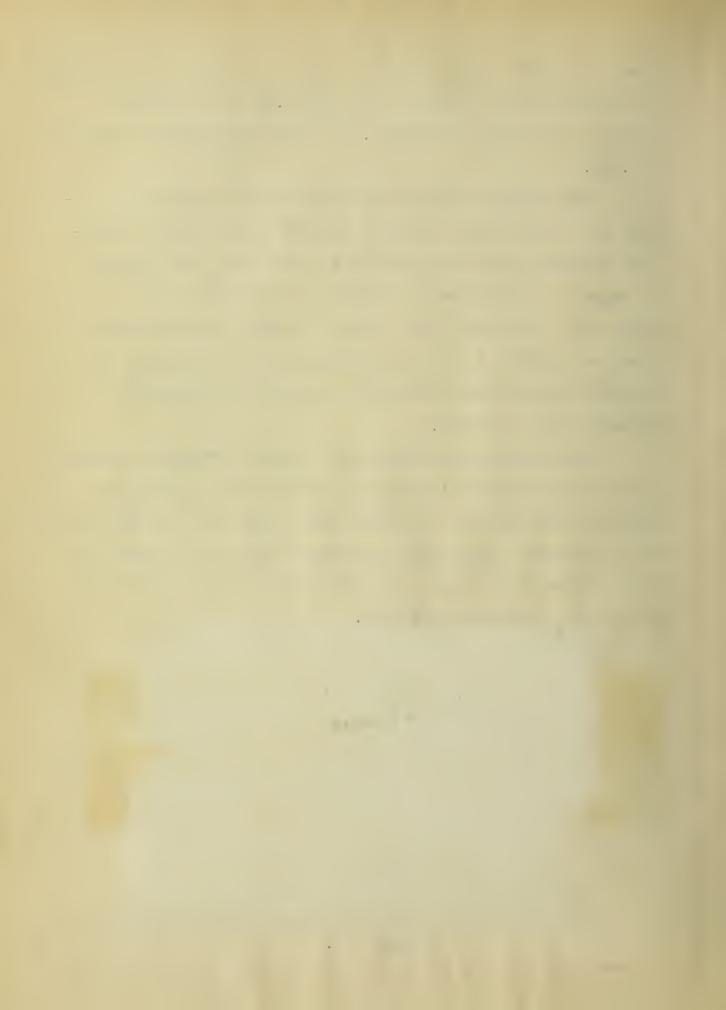
$$.45 \ E \qquad (31)$$

Thus a permanent field voltmeter, such as is ordinarily employed
on direct current circuits, would read .45 of the maximum
value of the rectified voltage. An actual test showed a reading
of .437.

The highest voltage obtainable with this form of recti-
fier is 77,700 volts, maximum value. At this tension, flash-
over occurred around the periphery of the disc, from segment
to segment, and followed the rotation of the disc in such a
manner as to indicate that a film of ionized air was carried
along on account of its own viscosity. Radial vent holes in
the discs caused freer circulation of air, and raised the
flashing point somewhat.

The second type of rectifier, shown in Figure 9, consists
of two brass rods, 30 inches long and 3/8 inch in diameter,
fixed at right angles, 15 inches apart along the hard oak shaft
which revolves in hard maple bearings. One rod is in each line
of the alternating supply, receiving its voltage through brass
slip rings, similarly as before.

Figure 9 .

Unidirectional voltage is taken from two sets of brass pole shoes, shown in the photograph, which are such length as to rectify 90° of the wave. The shoes can be lowered or raised to give any desired clearance from the rotating rods, and clamped in position. A clearance of about 1/4 inch was used in all our experiments. When the potential gradient across the gap between the rods and the pole shoes is sufficient to cause sparks to jump across, high frequency oscillations result on account of the capacity and inductance of the system. Figure 10 shows the discharge between the rods and the shoes, (a) being an instantaneous exposure, while (b) is a time exposure. It is noticeable that the spots which indicate the maximum points of the oscillations occur at about the same point in each revolution. Twelve dots can be counted over the length of the pole shoe, and as this represents 1/4 of a complete cycle, and as the frequency of the impressed electromotive force is 50, the frequency of the oscillations is thus seen to be 2400. The results here shown checked very closely with oscillograms taken at the same time.
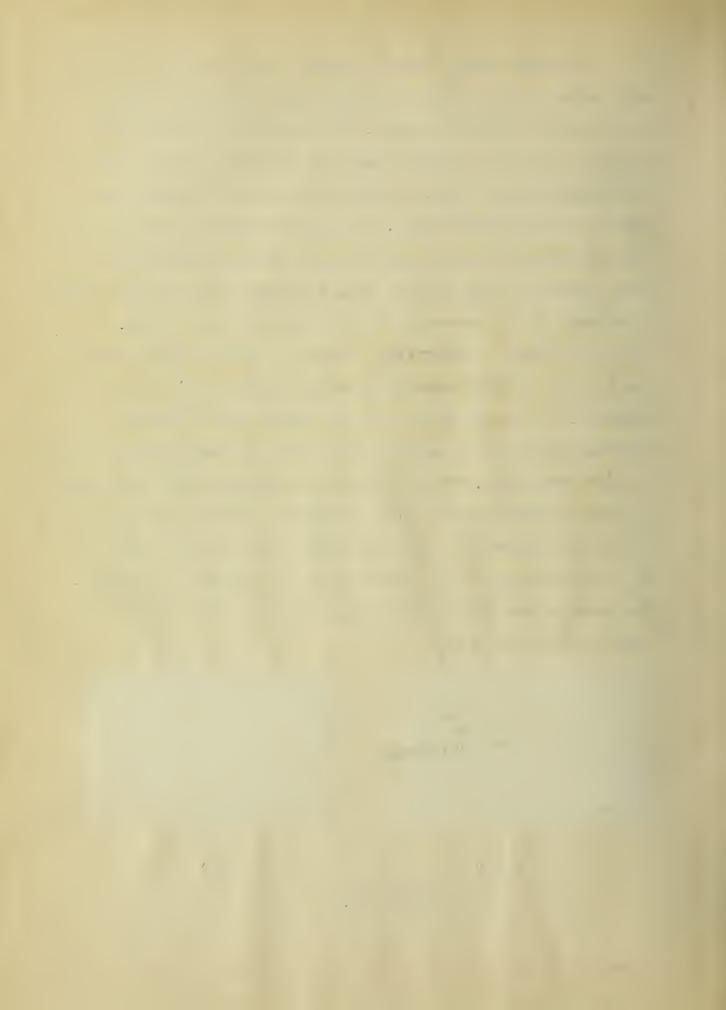

(a)   (b)

Figure 10.

The highest voltage obtainable with this machine is
106,000 volts, maximum value. At this voltage, flash-over occurs
between pole shoes of opposite polarity. Figure 11 is a dia-
gram of the connections used for taking oscillograms of the
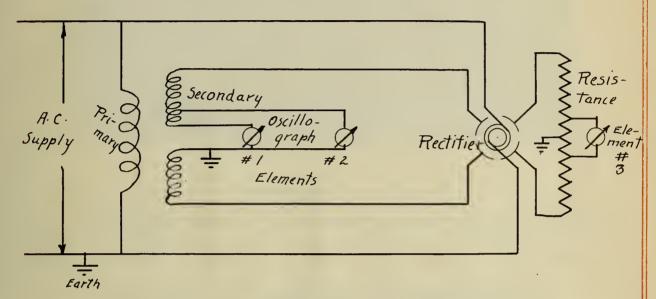high tension voltages and currents of this machine.

Figure 11.

The auxiliary winding of the transformer is used for
the alternating waves, while the rectified voltage is carried
through two sets of high resistance rods, grounded at their
center, and the oscillograph element shunted across a portion
of the resistance. The three resulting waves of alternating
voltage and current and of rectified voltage, or current, are
shown in Figure 12. The high frequency oscillations are very
apparent and make an analysis of the wave extremely difficult.
It will be noticed that the rectified wave is in phase with
the alternating current wave, which fact would be expected,
since the rectifier simply turns over the negative loop of
the current wave.

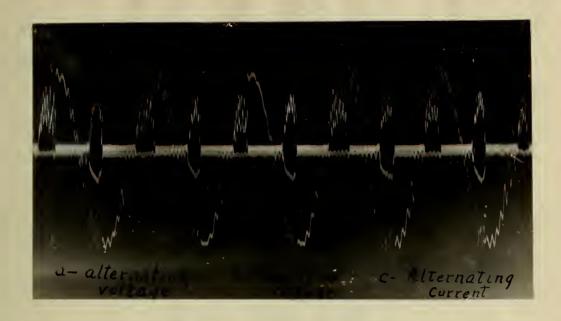a- alternating voltage   c- Alternating Current

Figure 12.

The third form of rectifier, together with the driving
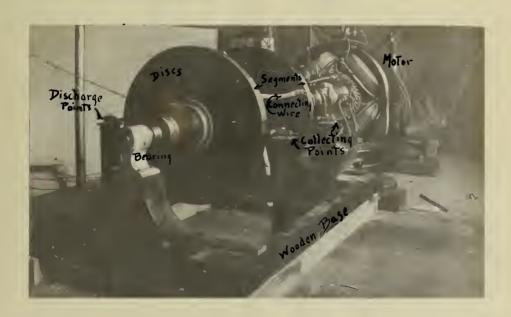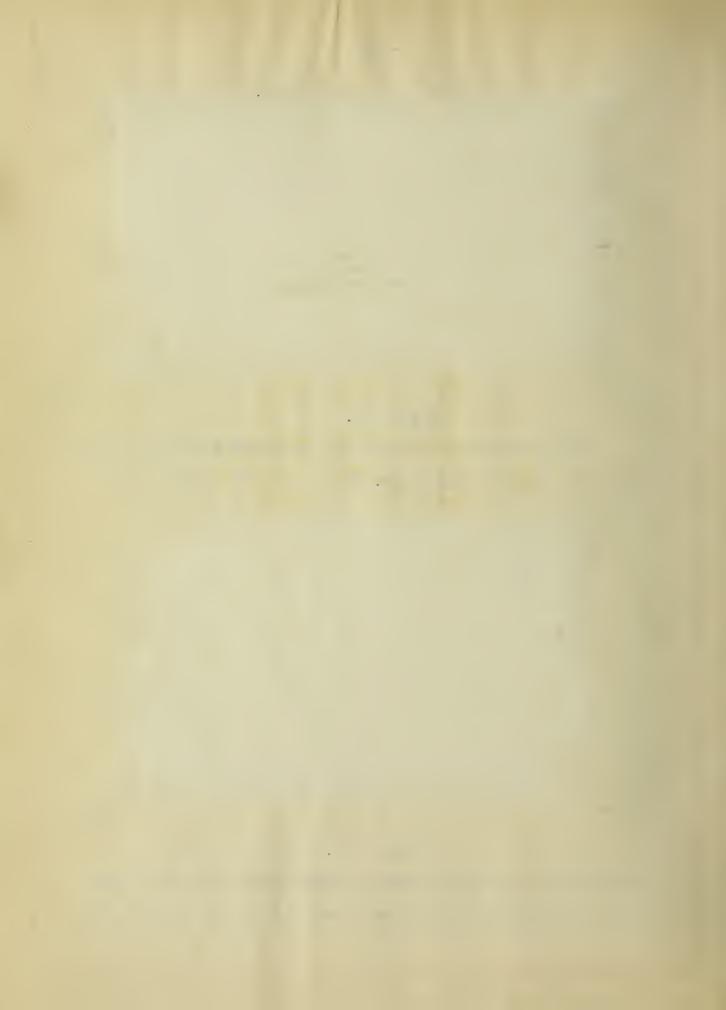motor, is shown in Figure 13. This is of the rotating disc-
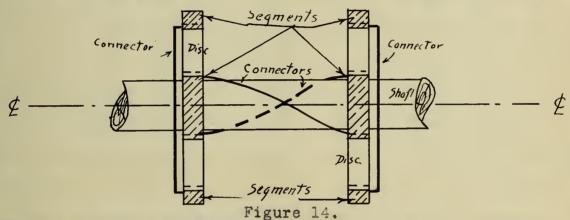

Figure 13.

non-contact type, alternating voltage being applied to two
sets of discharge points, one of which is dimly seen on the

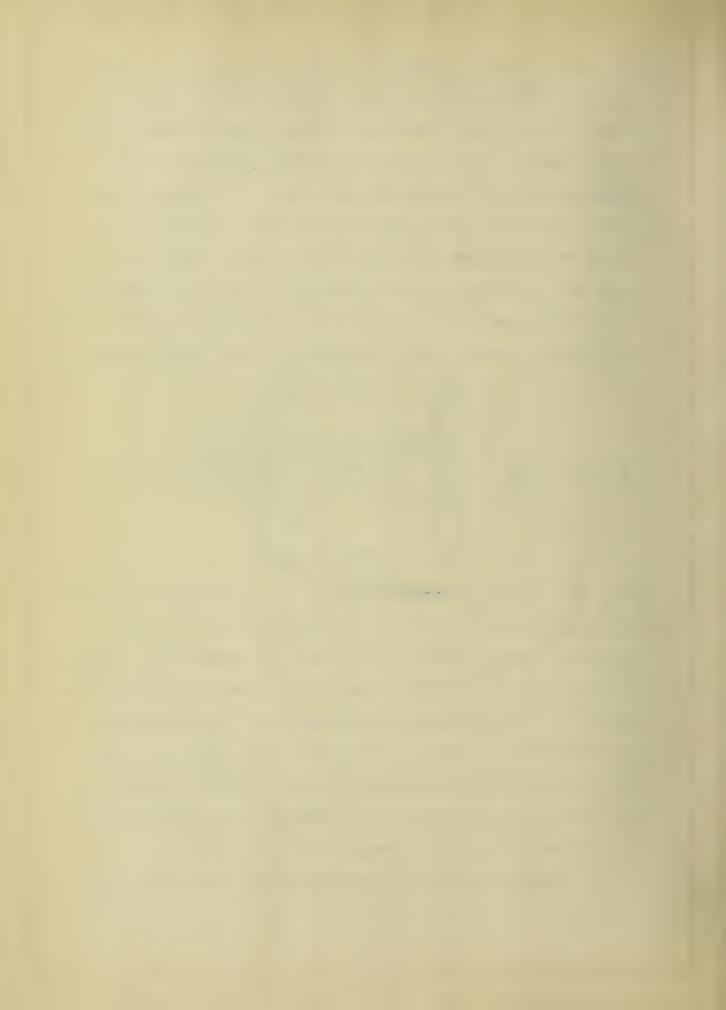left in the picture, while the rectified voltage is taken

from two similar points shown on the top of the posts at the

right of the discs. These discs are of dried poplar, 18 inch-

es in diameter, and 1 1/2 inches thick, spaced 14 inches

along the axis. They are fastened to a 4 inch wooden shaft

which revolves in metal bearings on metal journals. Four

raised brass segments on each disc, of such length as to rec-

tify 64° of the wave, show lighter just above the posts, and

are interconnected by # 10 rubber-covered wire encased in 3/16

inch rubber sheaths. The connections are as shown in Figure 14.

Figure 14.

From the nature of the connections, it is seen that flashover

must occur around one-half the periphery of the discs, or

from one discarge point to the other, as segments of opposite

polarity are on opposite sides of the discs. It is this fea-

ture of the rectifier that increases its insulating value,

and permits of a voltage of 184,000 volts, maximum value,

being applied before breakdown occurs. The great weight of

the machine is, however, objectionable, as a comparatively

large amount of power is required to drive it.

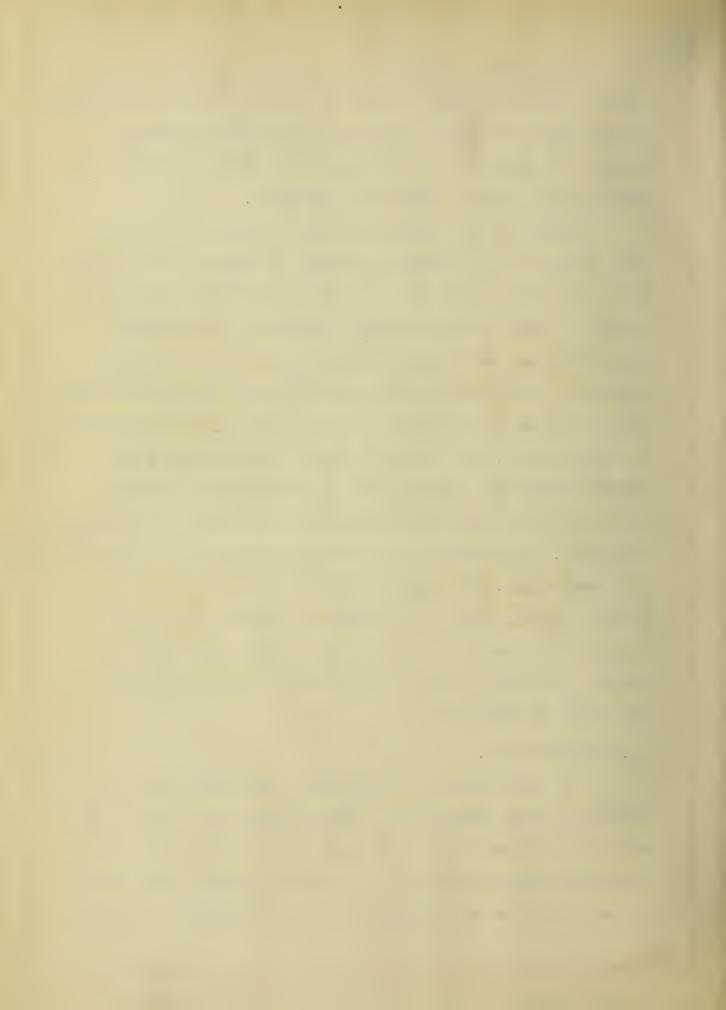From an electrical standpoint, the insulation, and

from a mechanical standpoint, the serviceability, of a rec-
tifier are the deciding factors in its design. On this account,
a combination of the second and third types, making a
light, serviceable, and well-insulated machine, without the
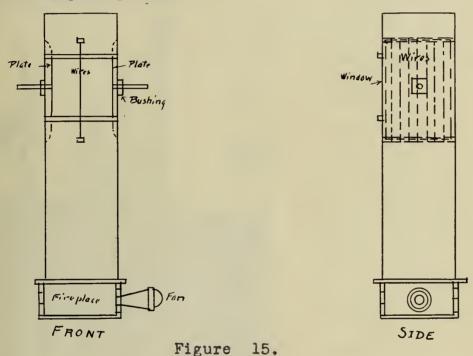use of wooden discs, would seem desirable.

Either of the rectifiers can be adjusted to rectify
any portion of the alternating wave, by shifting the relative
position of the revolving parts of the rectifier and of the
motor, by means of the adjustable coupling. Two methods of
determining the most desirable position for the parts are
plausible. The rectified voltage may be cut across high resis-
tance rods and a low-reading ammeter, the rods being grounded
at their center. The rotor may then be shifted until the
ammeter reads the highest value at any impressed voltage,
which indicates that the maximum portion of the wave is being
rectified. An ammeter on the alternating side will indicate
the same result. The second method is to adjust the parts
until a uniform spark is obtained over the entire length of
a pole shoe when the direct current brushes are short-cir-
cuited. The latter method is applicable only to the last
two types of rectifiers.

c - Precipitators.

The first form of precipitator used consisted of an
asbestos lined, wooden flue, 2 feet square and 10 feet high
with a window near the top through which the process of pre-
cipitation could be watched, and access gained to the elect-
rodes. This flue was placed over a brick fireplace in which
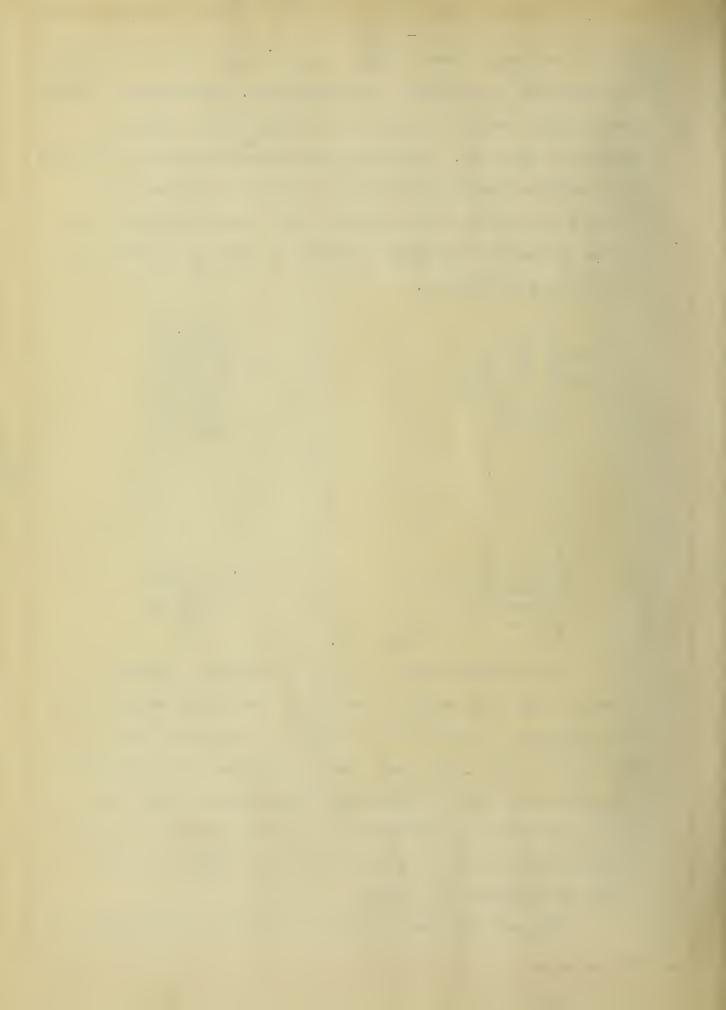
various materials were burned, and to which a draft of air
was supplied to accelerate conflagration. Figure 15 shows a front
and a side view of the apparatus with parallel wires and
plates in position. The plates and wires were held in position
by insulated bushings projecting through the sides of the
flue. As the gases passed up the flue, they were forced be-
tween the plates and wires, received a charge, and the heavy
particles precipitated.

Figure 15.

The next step was to use two concentric cylinders,
a small rough pipe within a smooth 10 inch pipe, supported
horizontally, with one end attached to the wooden flue op-
posite the window. The gases were forced out this pipe from
the flue, and thus the effect of various pipe lengths and
of the variation of the amount of precipitate with the dis-
tance through which the gases pass in the electric field,
could be conveniently studied.

The next step was to erect the concentric cylinder

electrodes vertically in order to correspond as nearly as possible with a commercial chimney. In this manner, the effect of the process on flue gases could be studied more advantageously. Both electrodes were insulated from the ground and from the fireplace beneath, by resting them on an insulating box. Figure 16 shows the method of supporting the pipes. A 2 inch pipe is shown as the inside electrode, this being used to give rigidity to the apparatus. The same principle applies to this as would apply to a smaller wire, but a lower voltage is require here than would be required with the smaller wire.
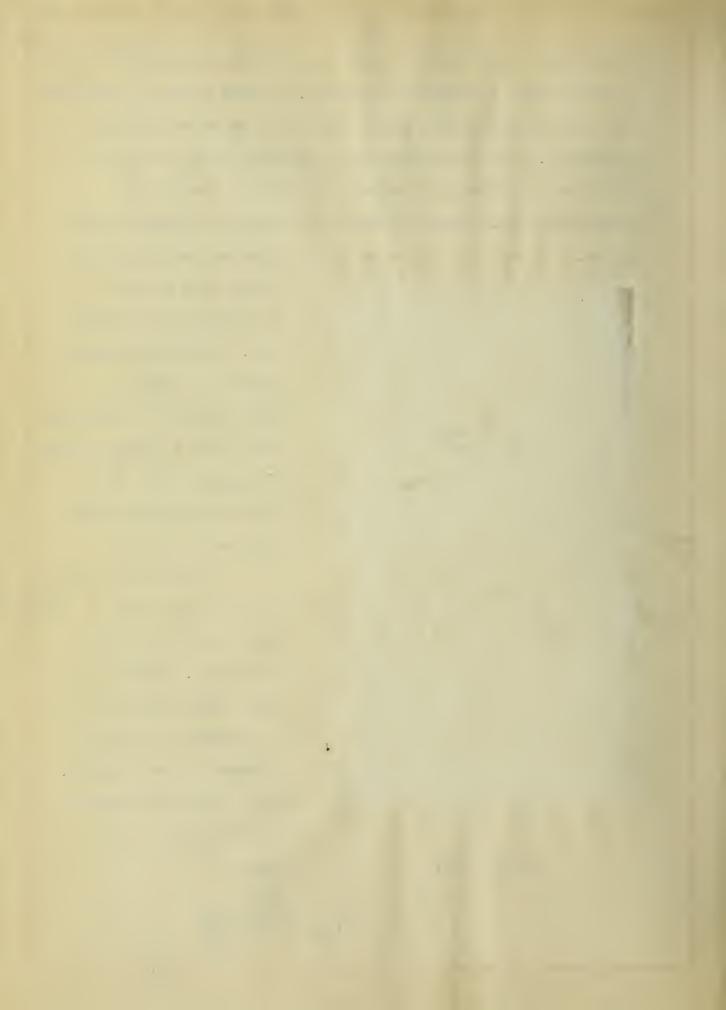
A flash-over can be seen occurring at the top of the pipe to the right. Voltage was just being applied, and a dangerous value was reached for an instant. The insulating support at the bottom is not seen.
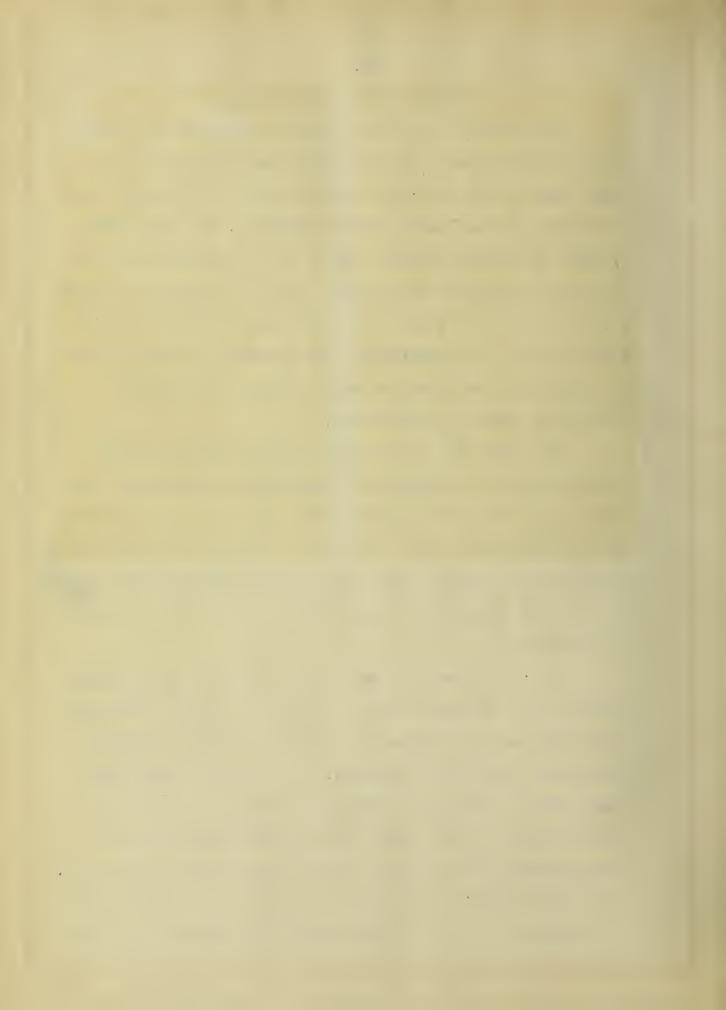
Figure   16.

IV.

Precipitation Experiments.

The action of the three types of rectifiers insofar as the resulting wave is concerned, was practically the same, hence, more extensive use was made of the second type on account of its lower power consumption. The concentric cylinder principle was made use of for a precipitator, as the results obtained with either this or the parallel wires and plate type are practically the same, and this form was more suited to our conditions. The adaption of either form in commercial installations would depend on the local conditions actually encountered.

The character of the fumes is the deciding factor for the material of which the electrodes are composed, corrosive gases requiring special attention. The most corrosive gas encountered was that from which $H_2 S O_4$ was precipitated, and for this, either a lead pipe and asbestos-covered wires, or tile with a stream of water flowing over it were used as electrodes.

A 3 foot pipe had very little effect on the composition with the voltage either on or off. A 10 foot pipe was next used, and with the small velocity of gases, precipitation was practically complete. The striking effect produced when the voltage is applied is shown in Figure 17, which gives two views taken a few minutes apart with the same exposure, but with the voltage respectively off and on. The length of pipe to be used is dependent upon the velocity of the gases in the flue upon which precipitation is to be
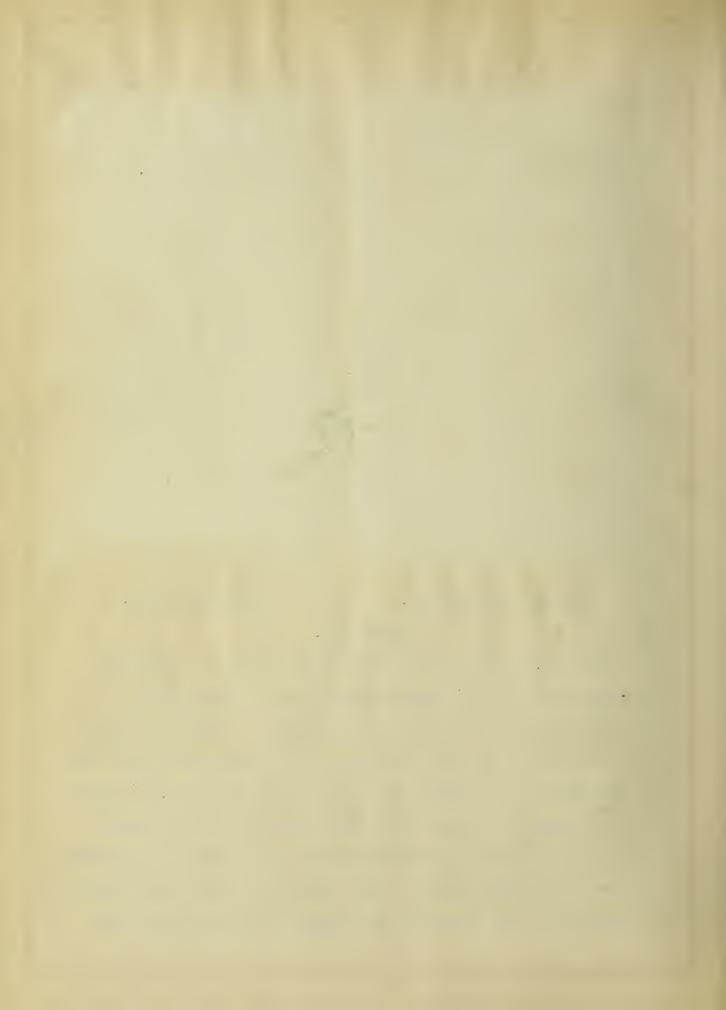
Voltage Not Applied.   Voltage Applied.

Figure 17.

performed. A strong draft will carry along the particles
even after they are agglomerated, and the pipe must be
long enough that the path of the path of a particle, which
is determined by the resultant of the electrical force and
the force of the draft, will end within the pipe. No appar-
ent stoppage in draft other than that due to the presence
of the electrodes themselves within the pipe was noticeable
when voltage was applied. The movement of the gases from the
negative to the positive electrodes can be plainly seen,

being more pronounced at the end where the gases enter the
field.

In order to show the relative amounts of precipitate
at various points after the gases had entered the flue, strips
of light paper the length of the pipe were attached to the
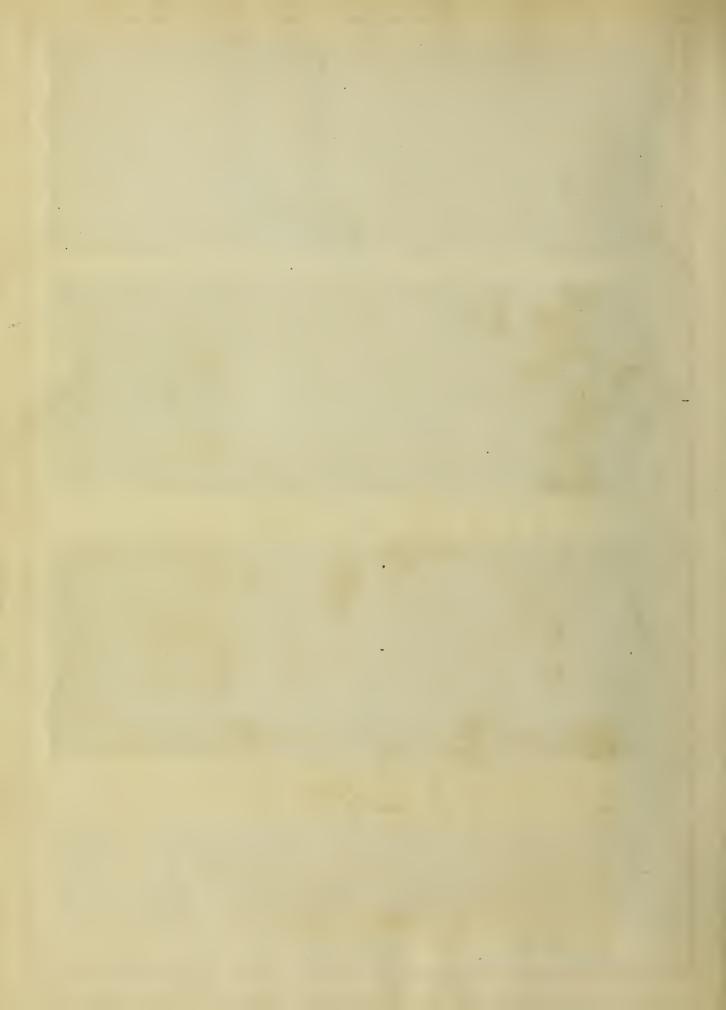inner surface of the larger pipe. The hydrocarbons from coal
and oils gave a brown deposit on this paper, shading from a
very dark brown at the point where the gases enter to an
almost white at the point of leaving. The shading seems to
follow somewhat a hyperbolic law, but this would evidently
be influenced by the velocity at which the gases move.

As has been pointed out under II, best results are
obtainable when the inside wire is used as the negative or
precipitating electrode, while the outside pipe is the posi-
tive or collecting electrode. The effect of the reversal of
polarity is shown in Figure 18, (a) and (b), which are
samples of the paper inserted when combustion had gone far
enough that almost all the hydrocarbons had been burned out
of the coal. Figure 18 (c) is a sample taken a short-time
before (a) and (b), with the rod negative. (a)was taken when
the rod was the negative electrode, and (b) when the pipe
was the negative electrode. These samples were all taken
near the center of the pipe with a voltage of 40,000, effec-
tive value applied for four minutes. In a similar manner,
the variation of voltage and the amount of precipitate was
studied, and the results seem to agree with the theory,
namely, that the velocity of precipitation is proportional

(a)

(b)

(c)

Original Paper.   Figure 18.

to the square of the voltage.

The power required was found to be very small, being
practically equal to the corona loss. Table I gives the
results of a typical loss test, while Figure 19 is a graph-
ical representation of the same.

Figure 20 is a typical oscillogram taken from the
apparatus under working conditions, showing the impressed
voltage and current and the rectified voltage. Figure 21
shows the primary, secondary, and rectified voltages. It
is noticeable that the high frequency oscillations set up
by the spark gaps are carried back to the primary of the
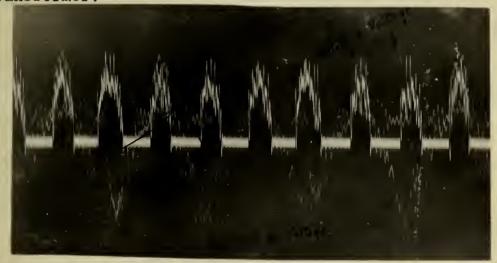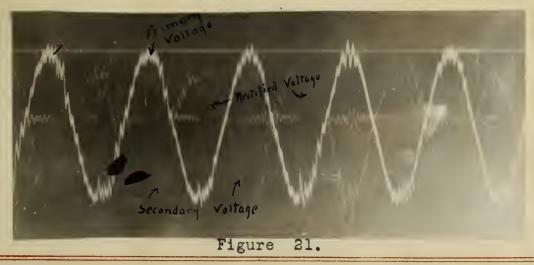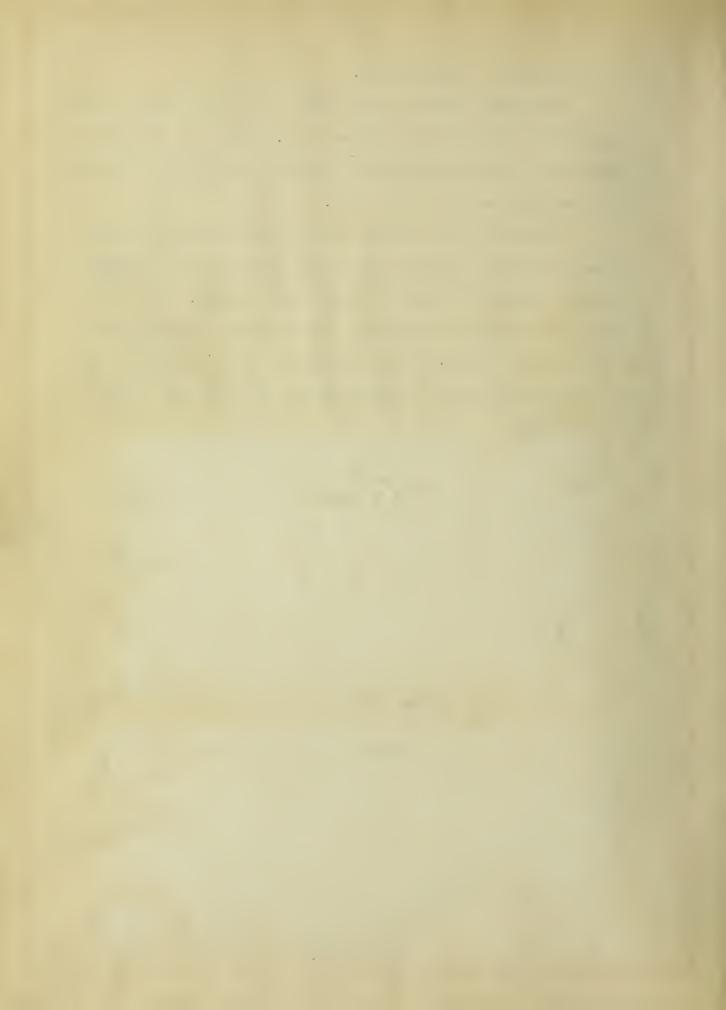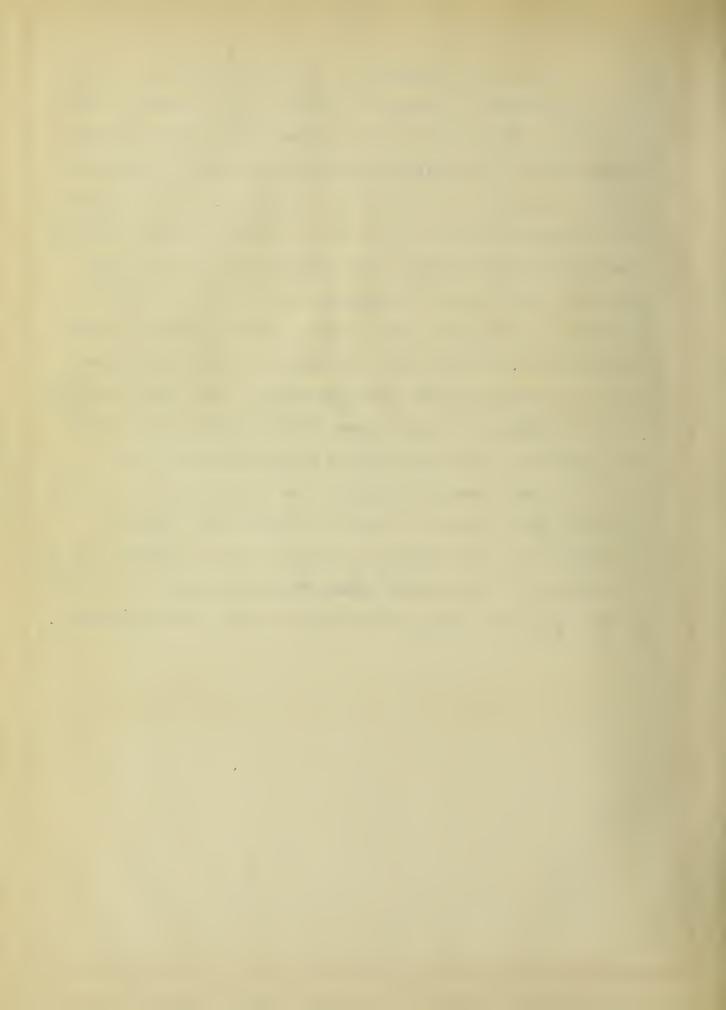transformer.

Figure   20.

Figure   21.

It is often impossible to have an auxiliary winding
on a transformer for reading voltages on the secondary side,
and since readings taken on the primary side are not always
indicative of the maximum value of voltage on the secondary
side, use might well be made of a spark gap. For this purpose,
an apparatus similar to that used by the Westinghouse Electric
and Manufacturing Company, and described by Messrs. Chubb
and Fortescue in the Proceedings of the American Institute
of Electrical Engineers for February, 1913, was found very
satisfactory. Ten inch (25 centimeter) spheres were used,
and the results obtained were practically identical with those
obtained by the above gentlemen. Table II gives the results
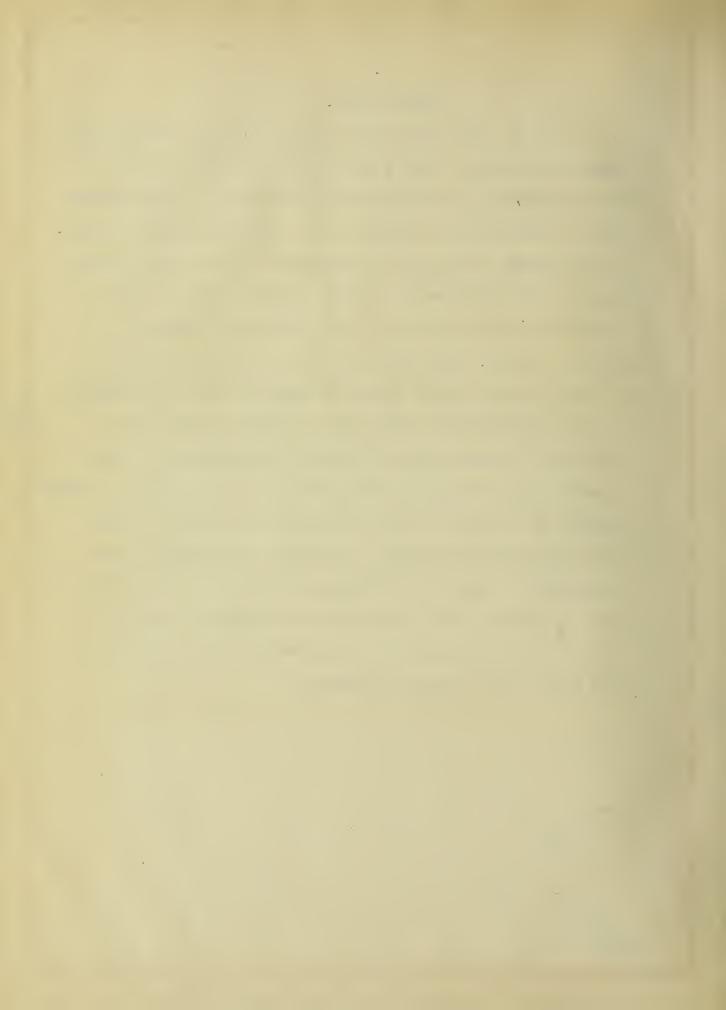of this test, while Figure 22 is a curve for this data.

It would seem advisable to use a condenser in parallel
with the precipitator in order to maintain the rectified
voltage wave and so prolong its effect, but our experiments
indicated that the natural capacity of the system is suffi-
cient, and that a separate condenser gives no better results.

V.

Conclusions.

It has been proved that the process of precipitating suspended particles from gases by means of high voltages is both **theoretically** and practically correct. It thus remains only to reduce the ~~the~~ process to a smooth commercial basis. The low power loss and the possibility of reclaiming byproducts by the application of this process indicate that it can be made to not only pay for itself, but actually to return a profit. Its application to smelters and refiners for ridding their waste gases of dangerous materials seems to offer an extensive field for the process. Also, the clearing of furnace gases for use in gas engines presents a particularly lucrative field, while a solution of the smoke problem in our large cities will seem to have been found when commercial apparatus , universally applicable, has been adopted. There are still many problems in connection with the process that must needs be worked out, but it is the hope of the writer that the present thesis may form a firm ground for future development.

VI.

Bibliography.

Corona and Dielectric Strength of Air - F. W. Peek -

    General Electric Review- December, 1912.

The Law of Corona and the Dielectric Strength of Air - Peek-

    Transactions of A. I. E. E. , 1910, '11, '12, '13.

The Electric Strength of Air- I ± II - III - IV- Whitehead-

    Transactions of A. I. E. E. , 1910, '11, '12, '13.

The Sphere Gap as a Means of Measuring High Voltage - Peek-

    General Electric Review, May, 1913.

Potential Stresses in Dielectric Mediums - Osborne -

    Proceedings of A. I. E. E., October, 1910.

Application of Theory of Electrosatics in High Voltage Inves-

    tigations - Fortescue.

    Proceedings, A. I. E. E. ,March, 1913.

Calibration of a Sphere Gap Voltmeter - Chubb and Fortescue-

    Proceedings of A. I. E. E., February, 1913.

The Sphere Spark Gap - Farnsworth and Fortescue -

    Proceedings of A. I. E. E., February, 1913.

Disruptive Strength of Air - Hayden and Steinmetz-

    Transactions of A. I. E. E., Volume XXIX, 1910.

The Positive and Negative Corona and Electrical Precipitation

    Proceedings of A. I. E. E.,June, 1913- Strong.

Precipitation of Smoke - H.W.Holmes -

    Electrical World, February 22, 1913.

Electrical Precipitation of Suspended Particles - Cottrell-

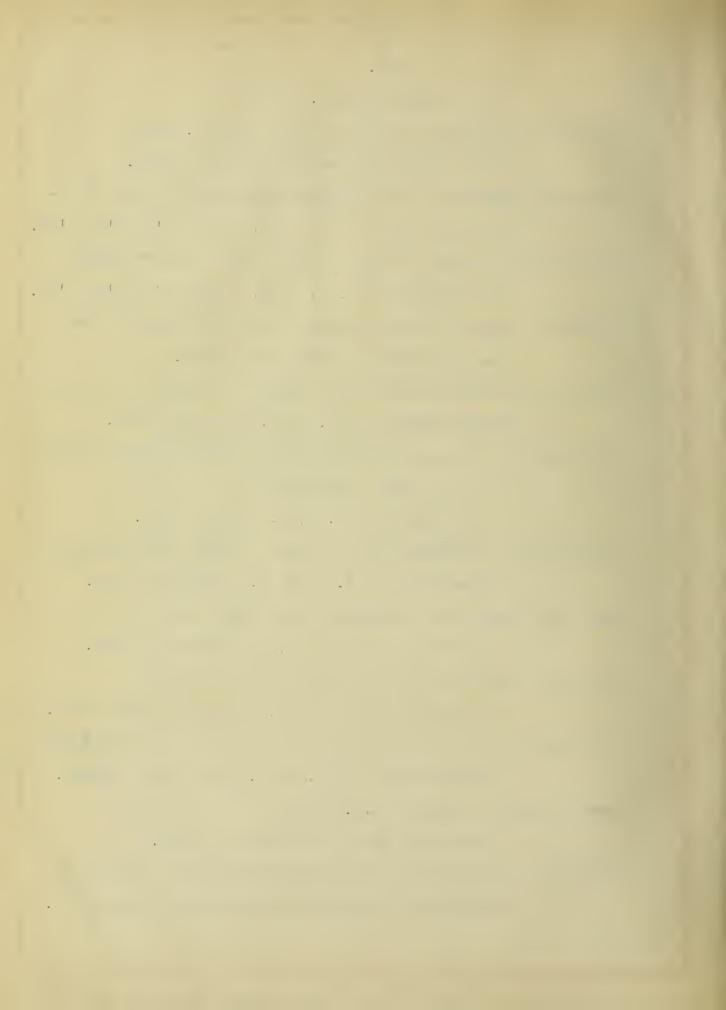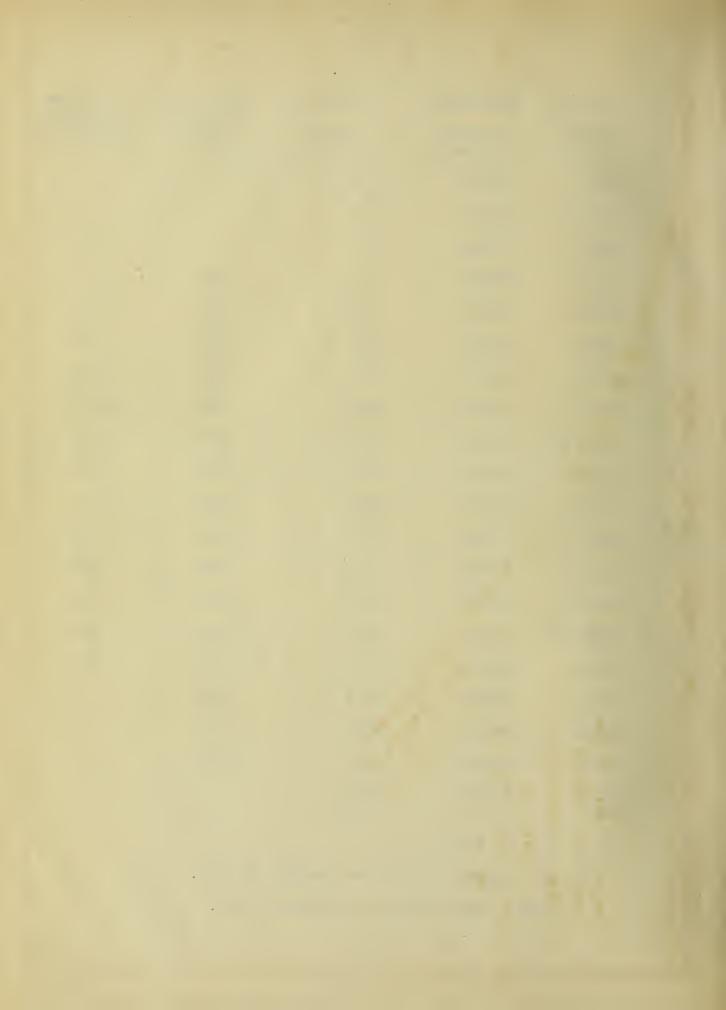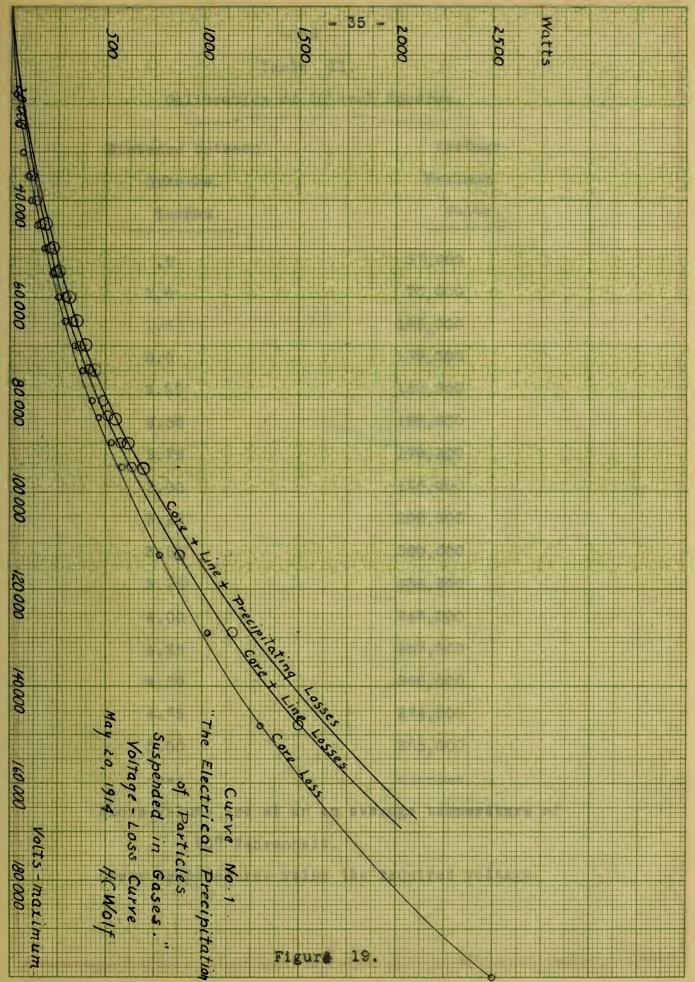   Industrial and Engineering Chemistry, Aug.,1911.

Table I.

Primary Voltage	Secondary Voltage	Core Loss Watts	Core Loss Line Loss Watts	Core,Line Precipitating Watts
18000	18000	20		
24300	24000	40		
30500	30000	60		
36000	35000	80	100	
41600	40500	114	128	140
46000	45000	148	168	188
51000	50000	180	204	228
56000	55000	220	228	262
61000	60000	258	290	300
65700	65000	292	332	340
71800	70000	340	372	400
76000	75000	380	422	450
81800	81200	432	492	488
85400	84800	465	505	555
91000	90000	525	583	622
96100	95200	584	640	700
114000	113000	784	885	
130000	129000	1024	1160	
148600	148000	1300	1500	
201000	200000	2505		

f = 50 cycles

All voltages given are maximum values.

Watts were read on the primary side.

Figure 19.

Curve No. 1.
"The Electrical Precipitation
of Particles
Suspended in Gases."
Voltage - Loss Curve
May 20, 1914   H.C. Wolf

Core + Line + Precipitating Losses
Core + Line Losses
Core Loss

Watts
2500
2000
1500
1000
500

20,000
40,000
60,000
80,000
100,000
120,000
140,000
160,000
180,000

Volts - maximum

Figure 19.

Characteristic Curve of Electrolytic Rectifier
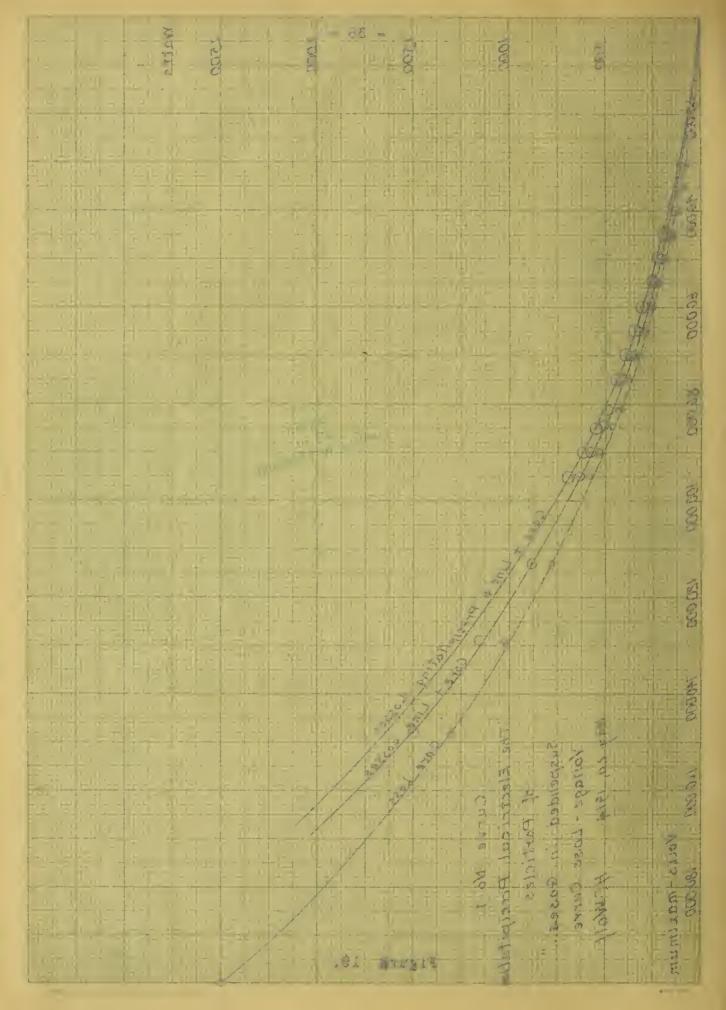
Table II.

Calibration of 10 inch Spheres.

Distance between Spheres. Inches.	Voltage Maximum Volts.
.5	37,000
1.0	70,000
1.5	105,000
2.0	139,500
2.25	156,500
2.50	168,200
2.75	179,300
3.00	195,000
3.25	209,000
3.50	220,000
3.75	232,300
4.00	246,000
4.25	257,000
4.50	269,000
4.75	274,500
5.00	285,000

Above Values are at an an average temperature of 60° Fahrenheit.

Lower temperatures raise the required voltage.

Curve No. 2
"The Electrical Precipitation
of Particles
Suspended in Gases."
Calibration Curve.
10" Spheres.

— H.C.Wolf —

⊙ Our Values

⊗ Westinghouse Values
(Max. Value)

Distance Apart
Inches

Figure 32.